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Naval Surface Warfare Center
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HAZARD DIVISION 1.2 TESTING IN A MINIATURE MAGAZINE

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As part of the Hazard Division (HD) 1.2 program sponsored by the Department of Defense Explosives Safety Board, a simplified version of the U.S. Army's Miniature Magazine was constructed and tested. This report describes the test structure and comments upon its constructability and cost. It then describes the HD 1.2 bonfire test that was conducted in the structure and gives the fragmentation/debris data produced by the event. Finally, it describes the thermal environment that was experienced within the structure.

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FOREWORD

This work was sponsored by the United States Department of Defense Explosives Safety Board as part of their ongoing research and development program. The simplification of the Miniature Magazine plans was performed by Mr. James Manthey of the U.S. Army Corps of Engineers, Huntsville Division. The structure was constructed by personnel from the Naval Air Warfare Center Weapons Division, under the direction of Mr. Carl Halsey. The test conduct and site cleanup were under the direction of Mr. Carl Halsey and Mr. Jackie Brown of the Naval Air Warfare Center Weapons Division. The instrumentation data collection and analysis was under the direction of Mr. Kent Rye of the Carderock Division of the Naval Surface Warfare Center. The thermal analysis of the structure was performed by Mr. Rodney Harris of the Naval Air Warfare Center Weapons Division.

Approved and released by:

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Director, Explosive Technology Application Division

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CHAPTER 1. BACKGROUND

The Miniature Magazine was designed under the auspices of the Safeload Program in the Office of the Project Manager for Ammunition Logistics (PM-AMMOLOG). The design work was performed by the Huntsville Division of the U.S. Army Corps of Engineers. The basis of design for the Miniature Magazine concept is described in Reference 1, which also presents construction details for the concept magazine.

Plans for two magazines were developed—one with a capacity of 68 kg (150 lb) and one with a capacity of 181 kg (400 lb) of hazard division (HD) 1.1 material. In both designs, the majority of the material is stored in a central compartment with lesser amounts stored in two side compartments. The two side compartments are totally isolated from each other and from the central compartment. Because of its design, the maximum credible event (MCE) is limited to the largest amount of material stored in any one of the chambers. The Miniature Magazines were designed to store non-compatible munitions and were to have the capability to store HD 1.1, 1.2, 1.3, and 1.4 munitions.

When it was designed in 1994, the default inhabited building distance (IBD) was 204.2 m (670 ft) when storing less than 45.4 kg (100 lb) of HD 1.1 material; this distance increased to a minimum of 381 m (1,250 ft) when storing amounts greater than 45.4 kg (100 lb). The Miniature Magazine was designed to reduce these required IBDs.

Because of its design, the Miniature Magazine provides heavy confinement for all materials stored within it. For this reason, it was chosen as the test structure for a trial to determine the effects of HD 1.2 ammunition stored under heavy confinement. The trial, as planned, was to have two objectives:

1. Determine the bonfire response of HD 1.2 105-mm ammunition inside a magazine with extreme confinement and compare this response with that obtained from previously conducted open air testing. It was hoped that these results would demonstrate the feasibility of using open-air test responses (for HD 1.2 ammunition) for establishing quantity-distance criteria for HD 1.2 ammunition stored inside structures.

2. Determine the debris hazard for a bonfire test in the Miniature Magazine filled with HD 1.2 105-mm ammunition. This information would be used to establish the minimum HD 1.2 quantity-distance criteria for the Miniature Magazine for ammunition with a MCE equivalent to (or less than) 105-mm ammunition.

The remainder of this report describes the magazine as it was constructed and then details the trial that was conducted and the results that were obtained. In addition, it provides an analysis of the thermal effects on the structure.

CHAPTER 2. TEST STRUCTURE

2.1 Structure Description

The smaller of the two magazine concepts was selected for construction and testing. Because it was to be used as a test structure, the Huntsville Division was asked to simplify the design and thereby reduce the cost by eliminating all non-essential elements. In their simplified design, the two side compartments were eliminated and the concrete fragment barricade located at the front of the structure was replaced with a plywood wall and an earthen barricade. In addition, such items as lightning protection and electrical systems were also eliminated. Their revised specifications are presented in Reference 2.

As constructed, the storage chamber had dimensions of 2.13 by 2.44 by 2.13 m (7 by 8 by 7 ft) (length by width by height), corresponding to a chamber volume of 11.1 m^3 (392 ft^3). The chamber had 0.30-m (1-ft) reinforced-concrete (RC) walls and a 0.46-m (1.5-ft) RC floor and roof. The chamber "box" was surrounded by 0.61 m (2 ft) of sand on the sides, rear, and top. There was a 0.30-m (1-ft) thick by 6.4-m (21-ft) long by 1.83-m (6-ft) wide RC canopy extending from the roof at the front wall of the chamber that stopped just 12.7 mm (1/2 in) short of a 2.74-m (9-ft) high (from ground level) single-revetted barricade facing the magazine.

The central storage compartment had three vents—one out the rear wall exiting through the top of the dirt fill (via a 90-degree turn) and one on either side of the front door near the floor. The vents on the front each had dimensions of 15.2 by 61 cm (6 by 24 in). The roof vent was circular and had a diameter of 20.3 cm (8 in). There was a door in the front. Its dimensions were 1.3 by 2.08 m (51 by 82 in). (Note: The door was left open for the test.) A general layout is shown in Figure 2-1. Once the earth fill is placed around the structure, there is not much to observe externally. Figure 2-2 is a photograph taken from the rear of the structure.

The construction process is detailed in a series of photographs presented in Appendix A.

2.2 Comments on Construction

The test structure, which was considerably simplified from the full magazine design, cost about $70,000 to build at China Lake, CA. It was constructed by Naval Air Warfare Center (NAWC) personnel. Estimates of $110,000 and $130,000 were received from commercial contractors for the same construction. The construction was very time-consuming because of the amount of rebar required in such a small space. Construction was completed less than 30 days before the test was conducted. The specifications for the structure called for a 28-day curing time for the concrete. Because of delays in the construction, only 24 days elapsed between the pouring of the concrete and the test.

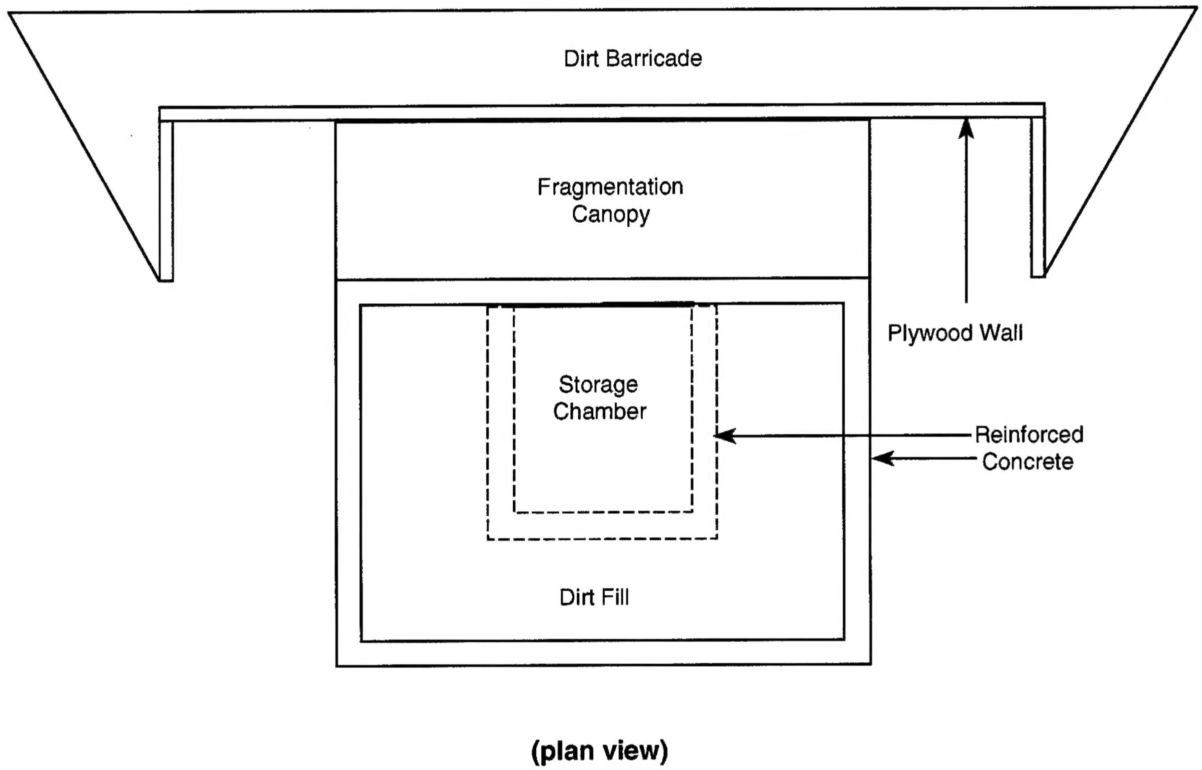

Figure 2-1. Miniature Magazine Test Configuration

Figure 2-2. Diagonal/Rear View of Test Structure

CHAPTER 3. TEST DESCRIPTION

Sixty boxes of M1 105-mm cartridges (120 rounds) with a net explosive quantity (NEQ) of 433.3 kg (955.2 lb) were utilized. If the propellant weight is not counted, then the NEQ of this item becomes 276.5 kg (609.6 lb). The explosive fill was Composition B. The rounds were fitted with aluminum nose plugs. A gap of at least 15 cm (6 in) was left between the boxes and the walls of the test chamber. A wooden frame was placed on the floor to provide the appropriate separation between the bottoms of the boxes and the floor. The total volume of the boxes was about 3.4 m^3 (120 ft^3).

The fire was started using approximately 38 liters (10 gallons) of gasoline ignited using exploding bridgewire headers (bridgewires without the explosives). The gasoline was placed in pans located beneath the wooden frame.

The test instrumentation included airblast (two legs of two gauges each), thermal (two thermocouples on walls, two in fire, two on rounds, and two in fuze wells), and video cameras (two). After the test, all fragments and debris were surveyed, identified, and weighed.

CHAPTER 4. RESULTS

4.1 General Observations

The test was conducted on 24 June 1996. The fire was ignited at 10:06:49 PDT. The first event occurred about 22 minutes after the fire was started. There were 35 major reactions (explosions with fireballs exiting the barricaded area and/or smoke plumes exiting the roof vent). The last event occurred about 2 hours and 33 minutes after the fire was started. The ventilation in the magazine was more than adequate for supplying a draft to feed the fire in the magazine. Generally, the earlier events tended to have a "metallic" sound, whereas the later ones tended to sound muffled, as if they were buried. One event was observed to occur at the edge of the barricaded area (apparently a round that had been kicked out before reacting).

Twenty-four hours after the test, the rounds remaining inside the structure were still too hot to handle. Forty-eight hours after the test, the magazine walls were still warm, even though it was cool (4 °C), windy, and raining at the test site. Seventy-two hours after the event, some of the unexploded rounds that had remained buried were still warm to the touch.

The external walls of the magazine (sides and rear) that held the sand around the storage compartment were undamaged, except for a very small hairline crack in the back. The inside surface of the chamber walls and ceiling were highly damaged—apparently from the thermal environment. The concrete surface appeared very porous and flaky, and in many places it showed evidence of extensive spalling to the depth of the first layer of rebar. At one location near the floor, the spall extended beyond the second layer of rebar. The bottom of the compartment was covered with spall debris, concrete powder, fragments, and intact rounds. The floor itself was completely destroyed. The roof had spall damage extending to the depth of the first layer of the rebar making it unsafe to work inside the structure. The outside surface of the front wall that was downwind from the opening for the front door was heavily spalled, whereas there was no spall damage on the outside wall surface upwind of the door opening. The same comment is true for the underside surface of the fragmentation canopy. A portion of the front wall of the storage compartment with dimensions equivalent to the width of the vent and the height of the doorframe was destroyed. However, the rubble remained in the barricaded area in front of the magazine. Figure 4-1 is a post-test photograph of the interior of the structure showing some of the damage to the floor, ceiling, and side wall.

The plywood retaining wall for the earth barricade that faced the magazine front wall was consumed by fire. The sand barricade lost about a foot in height because of the loss of the retaining wall, with the sand shifting towards the front wall of the magazine.

Figure 4-1. Damage to Inside of Structure

4.2 Debris Recovery

Thirty rounds were recovered unreacted. Some had melted explosives on the exterior of the projectile body and two rounds were glued together with melted explosive. Forty-seven empty (burned out) projectile bodies were recovered. Approximately 327.5 kg (722 lb) of projectile pieces (fragments) were recovered inside the magazine and in the sand and ashes just outside the door.

There was no concrete debris ejected from the structure. The farthest fragment throw was 204.2 m (670 ft); this item was a piece of projectile body. Its final position was in line with the opening on the side of the barricade. Two fragments had a range of about 91 m (300 ft), 9 fragments had a range of about 61 m (200 ft), 9 fragments had a range of about 30 m (100 ft), and 50 fragments had ranges of less than 30 m (100 ft). Figures 4-2 and 4-3 are plots of the recovered debris locations. Figure 4-2 presents a wide field and shows the locations of all of the recovered items; Figure 4-3 presents a more restricted view and concentrates on the region around the structure. Appendix B is a catalog that gives the location and description of each debris piece.

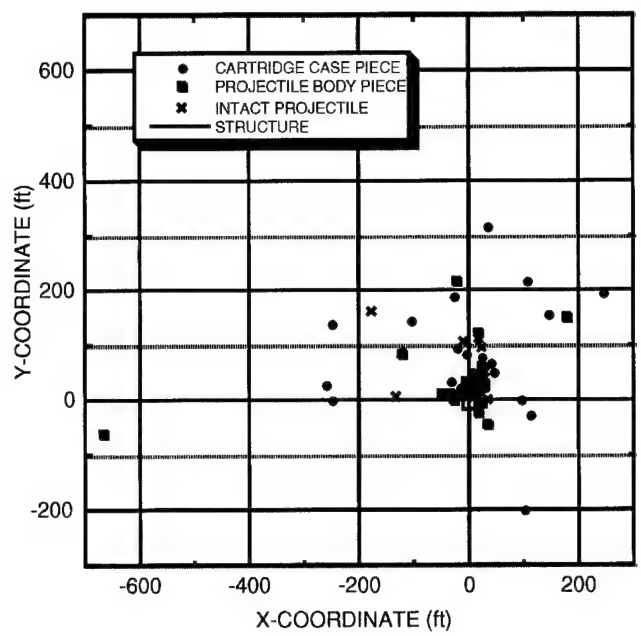

Figure 4-2. Debris Recovery—Wide View

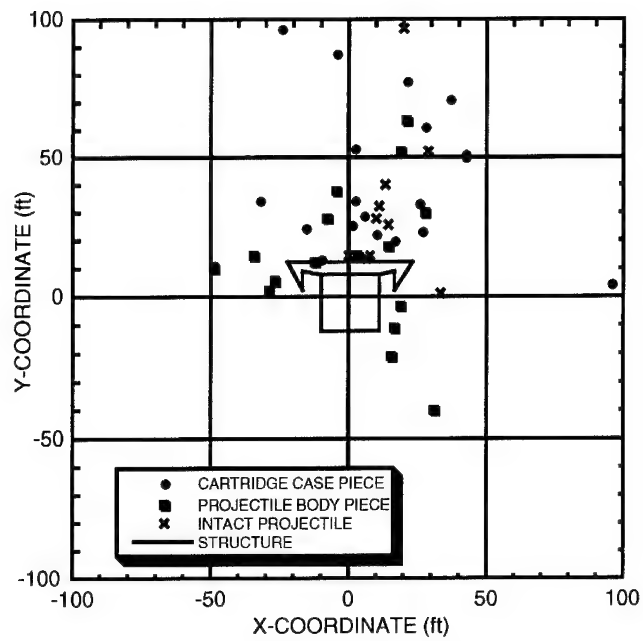

Figure 4-3. Debris Recovery—Narrow View

4-3. Inhabited Building Distance

The fragments and debris information presented in Appendix B were analyzed using the Modified Pseudo-Trajectory Normal (MPTN) methodology[3] to obtain the appropriate fragmentation IBDs. The results of this analysis are shown in Table 4-I.

Table 4-I. Fragmentation Inhabited Building Distances

Angle[a] (degree)	Direction	MPTN range (ft [m])
318.8–41.2	Front	94 (28.6)
318.1–0.001		84 (25.6)
0.001–41.2		103 (31.4)
41.2–138.9	Side	40 (12.2)
41.2–90.5		47 (14.3)
90.05–138.9		<35 (<10.7)
318.9–138.9	Rear	<35 (<10.7)
221.1–318.8	Side	46 (14.0)
221.1–269.5		<35 (<10.7)
269.5–318.8		59 (18.0)

[a]0 Degrees is out the front of the structure.

Based on the above analysis, for the as-built structure the following fragmentation IBDs for HD 1.2 ammunition with an MCE equal to or less than the M1 105-mm ammunition that was used on this test are recommended:

Front:	32 meters (105 feet)
Side	18.3 meters (60 feet)
Rear	10.7 meters (35 feet)

The loss of the plywood wall supporting the barricade out the front allowed some of the fragments to escape the structure. If this wall were replaced with a concrete one as called for in the original design, then the amount of fragments and debris that escaped the structure would be greatly reduced. However, with the current canopy/barricade design, a true zero quantity-distance probably cannot be achieved.

4-4. Instrumentation Results

The instrumentation results are presented in Appendix C. Due to the severe thermal environment exterior to the structure, several of the gauges malfunctioned on many of the events. Because of this and because no zero-time sensor was deployed (it was assumed that all events would be located inside the structure), insufficient information was generated to allow event yields to be determined. Appendix C presents the following information: (1) event times recorded by an on-site observer (Table C-I), (2) event times determined from the pressure records and a comparison with the on-site observer times (Table C-II), (3) airblast pressure and relative time of arrival measured for each event (Table C-III), and (4) thermocouple data (Table C-IV). Included in this appendix are figures that show the locations of the airblast transducers and the arrangements of the thermocouples within the structure.

As indicated in the previous paragraph, Appendix C also presents the results of the thermocouple measurements that were made. The maximum recorded flame temperature was 1,300 °C; the maximum recorded chamber wall temperature was 750 °C. In both cases, approximately 21.8 minutes of data were recorded after the start of the fire. At that time, the thermocouple instrumentation ceased to function.

Seventy-seven events were identified by the on-site observers and an examination of the airblast recordings (Tables C-I and C-II). Thirty-five of these events were considered significant reactions. Seventy-seven projectiles or projectile bodies were recovered intact; therefore, 43 rounds reacted in some manner. Since only 35 events were identified as significant, the remaining 8 events must be accounted for. These missing 8 events are included either as multiple round reactions or the reaction of rounds were buried so deeply when they reacted their apparent airblast was too low to be recorded.

CHAPTER 5. SUMMARY AND DISCUSSION

5.1 Summary

The M1 105-mm cartridges behaved in a manner similar to those tested in the open; that is, the structure appeared to have little effect on the HD 1.2 behavior of the test item. The elapsed time to the first reaction was similar to the times observed for stacks in the open. The "popcorn-like" nature of the reactions was also unchanged. As in the open-air tests, approximately one-third of the total number of rounds present in the stack reacted.

Although it was severely damaged, the structure survived the event. Thermocouples indicated that it was exposed to temperatures of over 700 °C during the first 22 minutes of the test. The majority of the observed damage was attributable to thermal effects rather than to blast or fragment attack. The fact that the concrete had cured for only 24 days instead of the required 28 days prior to the test did not significantly alter the response of the structure. Because the structure was severely weakened, it was unsafe to work inside it. It was also decided that it was uneconomical to try to repair it. Rather, the structure was razed at the end of the test.

Because the thermal environment proved so damaging, a thermal analysis of the event was performed to better quantify this phenomenon. This analysis was performed by NAWC. It indicated that the floor, roof, and most of the walls were exposed to temperatures of 760 °C (1,400 °F) at the start of the fire and 1,040 °C (1,900 °F) at the end of the fire. When these temperatures are applied to the concrete, it erodes to a depth of about 10-cm (4 in), the depth of the first rebar layer. This analysis is presented in Appendix D.

5.2 Discussion

The original concept of the Miniature Magazine was for a relatively inexpensive structure in which to store small amounts of material. As demonstrated by this program, even the "simplified" structure was quite expensive (over $70,000) and difficult to construct. There may be other alternatives available. The Naval Facilities Engineering Services Center has designed a modular magazine with a capacity of 500 pounds per module for a facility in Hawaii. When constructed in Hawaii, this facility cost about $50,000 per module. It is described in References 4 and 5. With a 500-pound MCE, this structure was designed to have an IBD of 1,250 ft to the front and 700 ft to the sides and rear. With a smaller MCE, these ranges could decrease significantly. Another alternative might be to modify a commercially available magazine. Such modifications would include but would not be limited to increasing the vent area, strengthening the door, and determining the proper amount of soil cover.

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4. Tancreto, James E., Hager, Kevin, and Wager, Phil, "Modular Ready Magazine Design For Reduced Explosives Safety Distances, *Minutes of the 27th DoD Explosives Safety Seminar*, August 1996.

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Appendix A

PHOTOGRAPHIC SEQUENCE TAKEN DURING CONSTRUCTION

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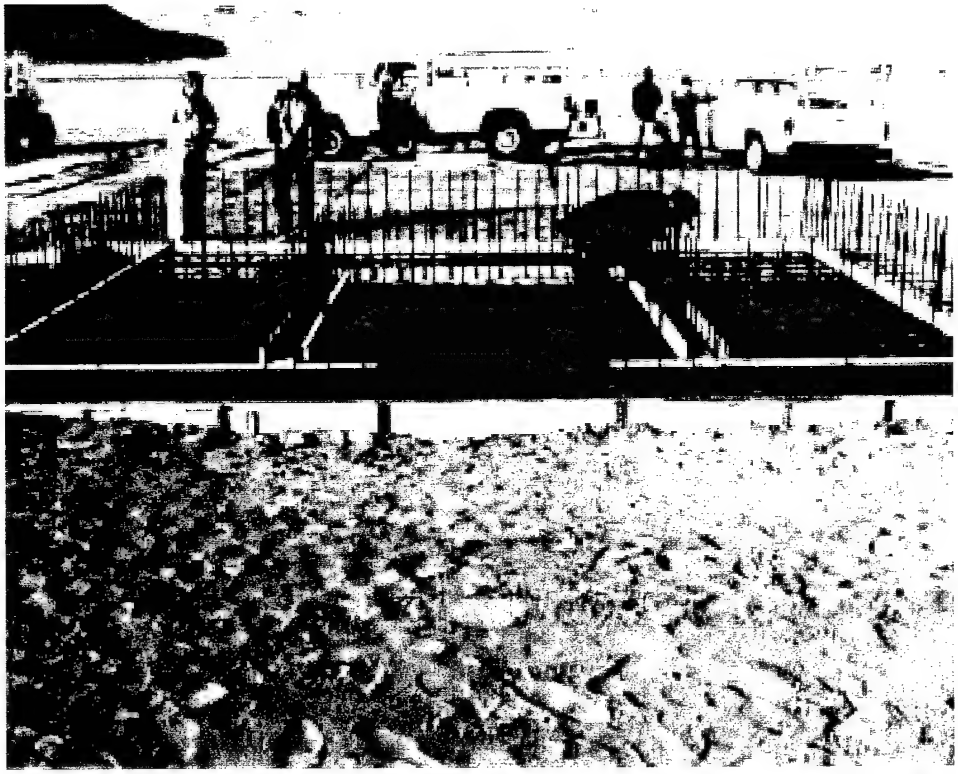

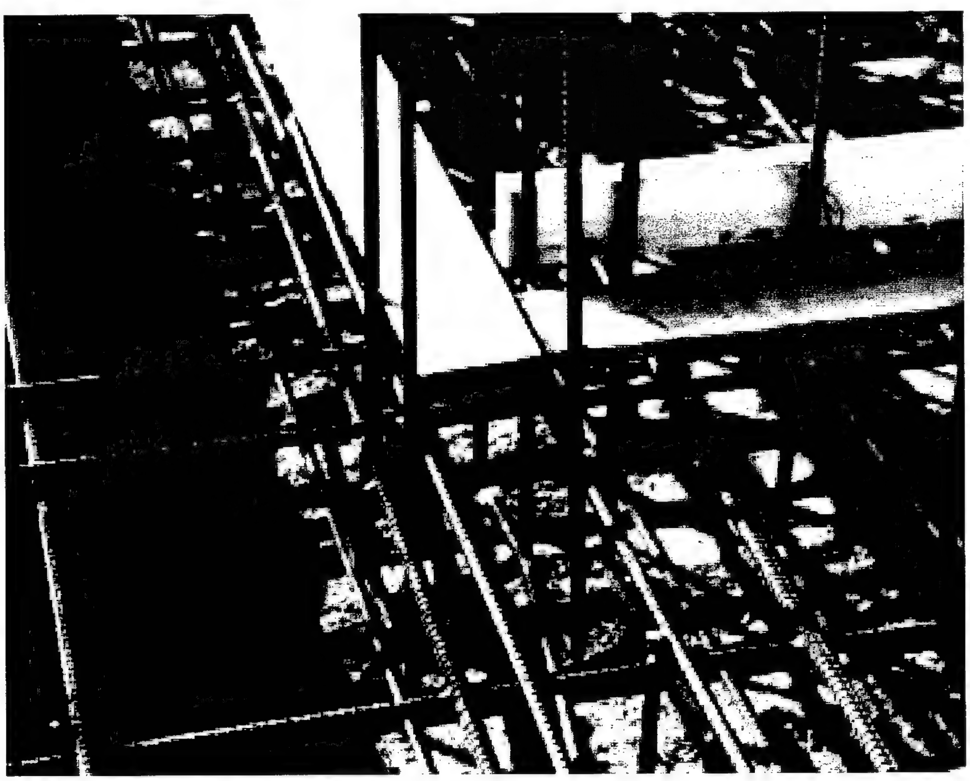

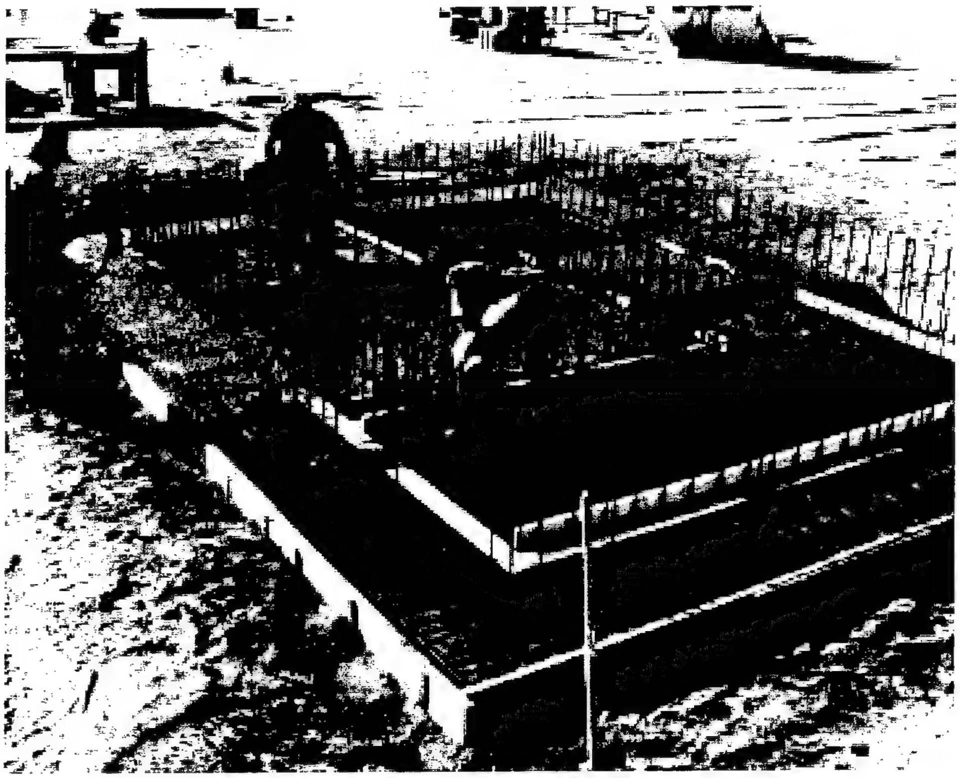

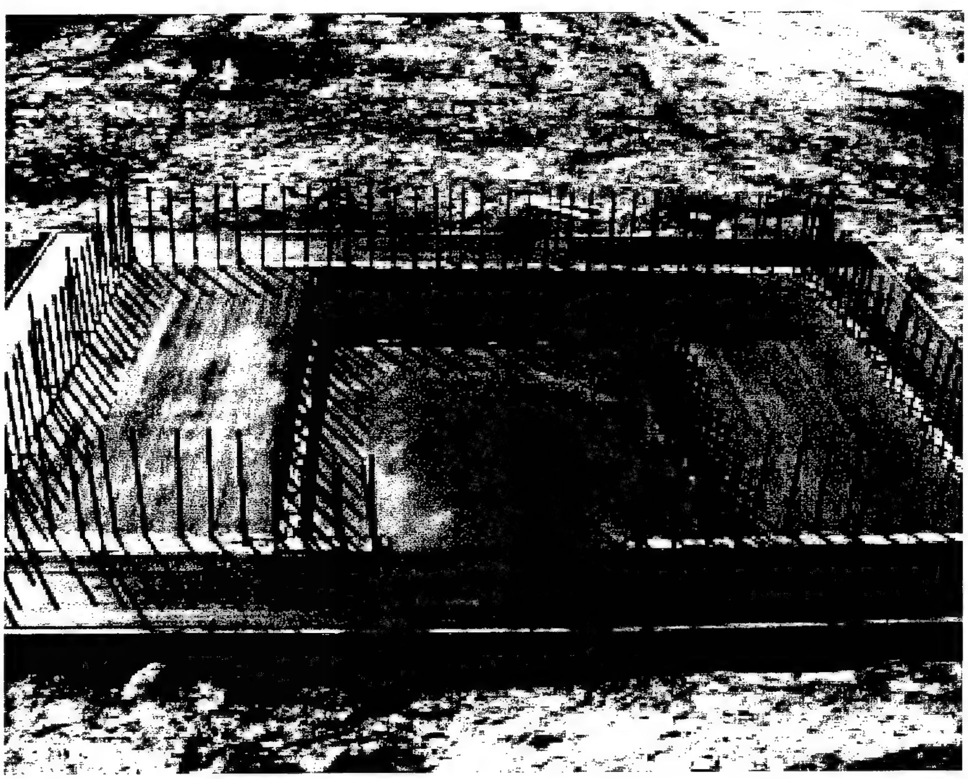

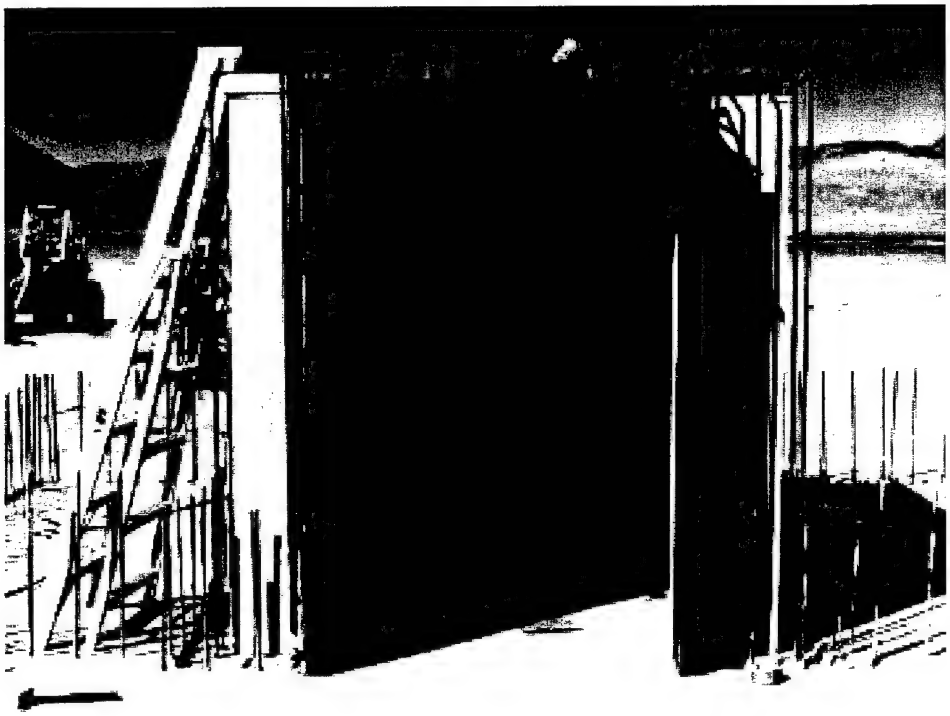

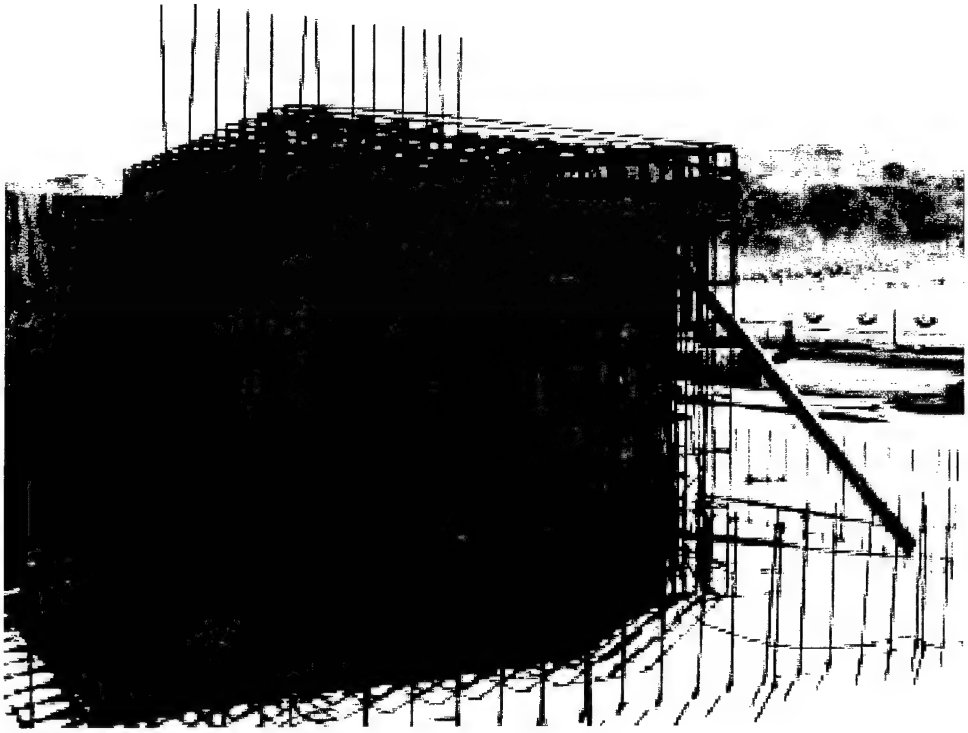

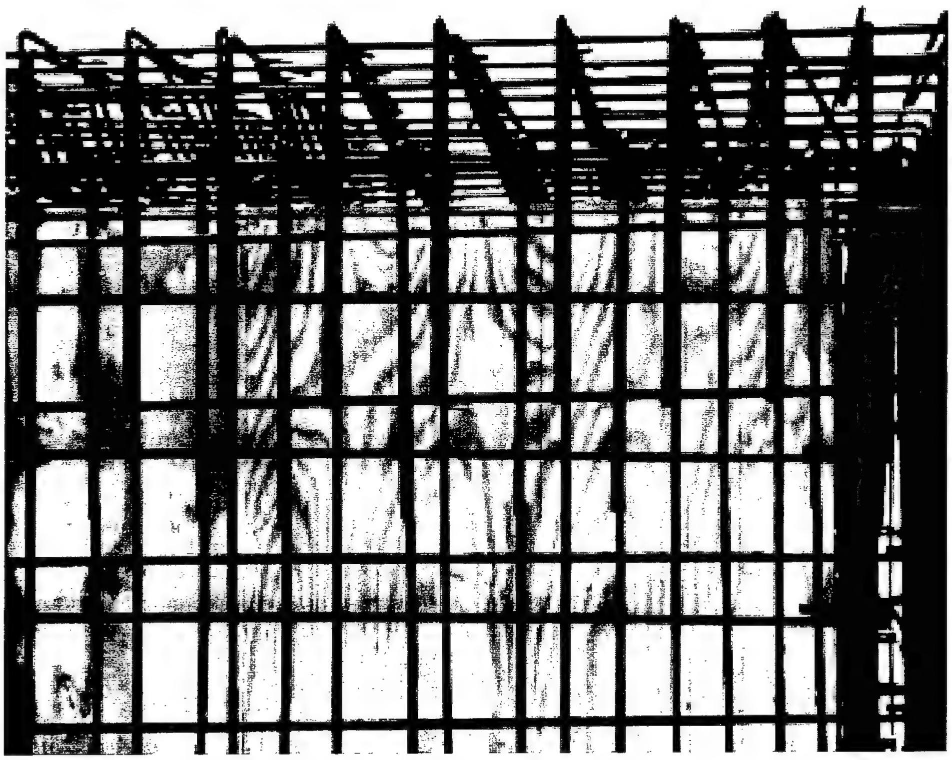

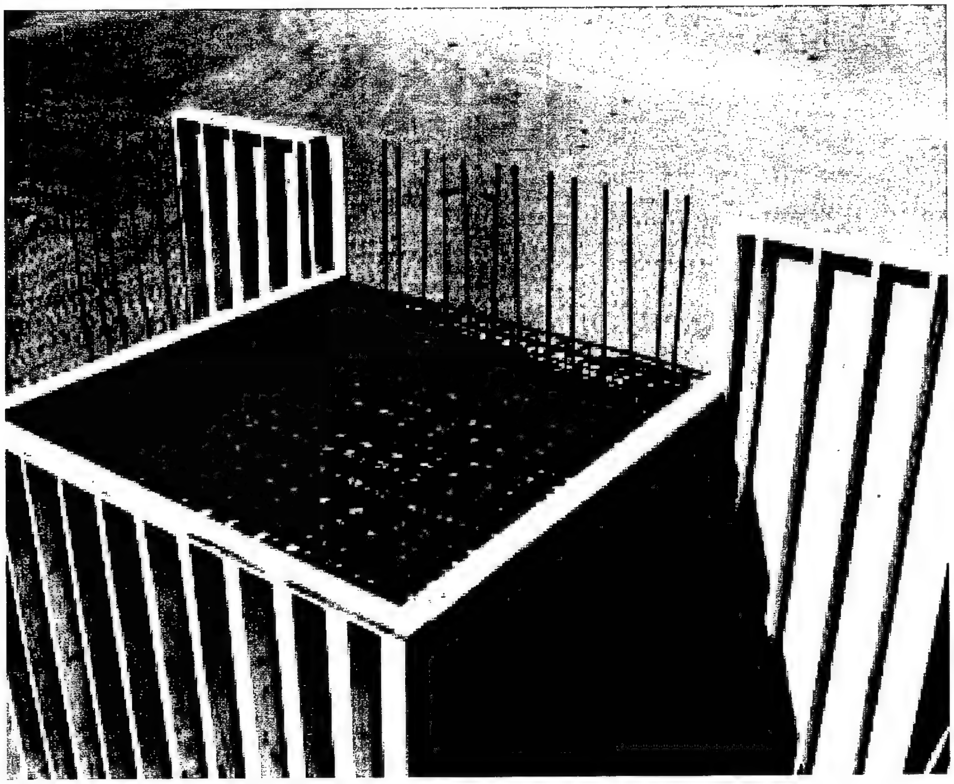

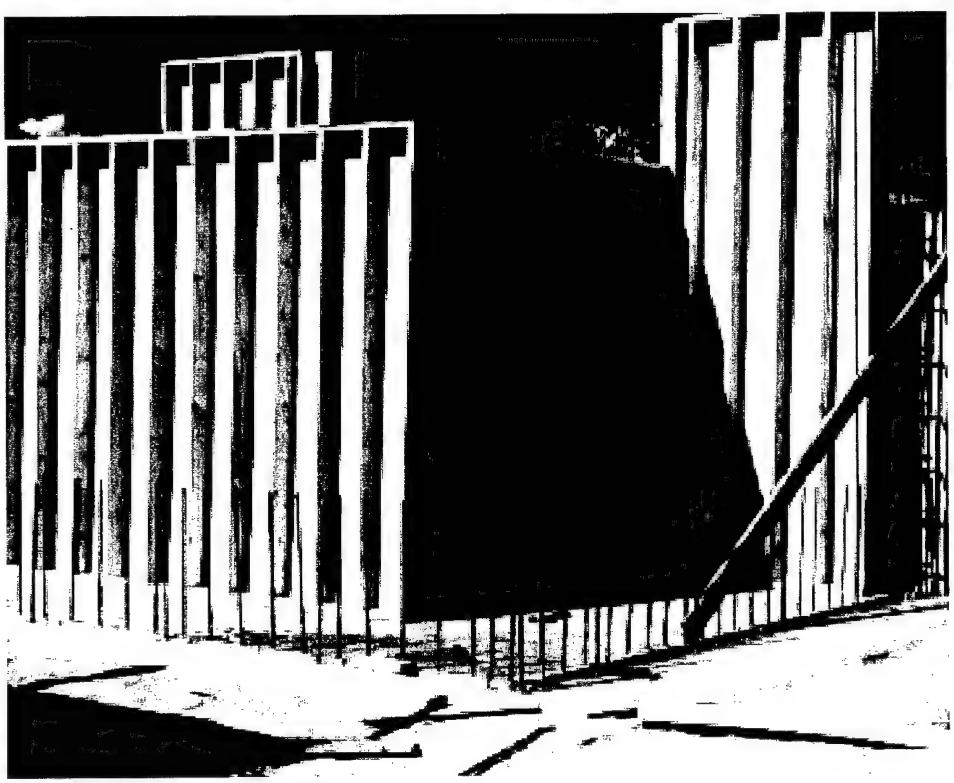

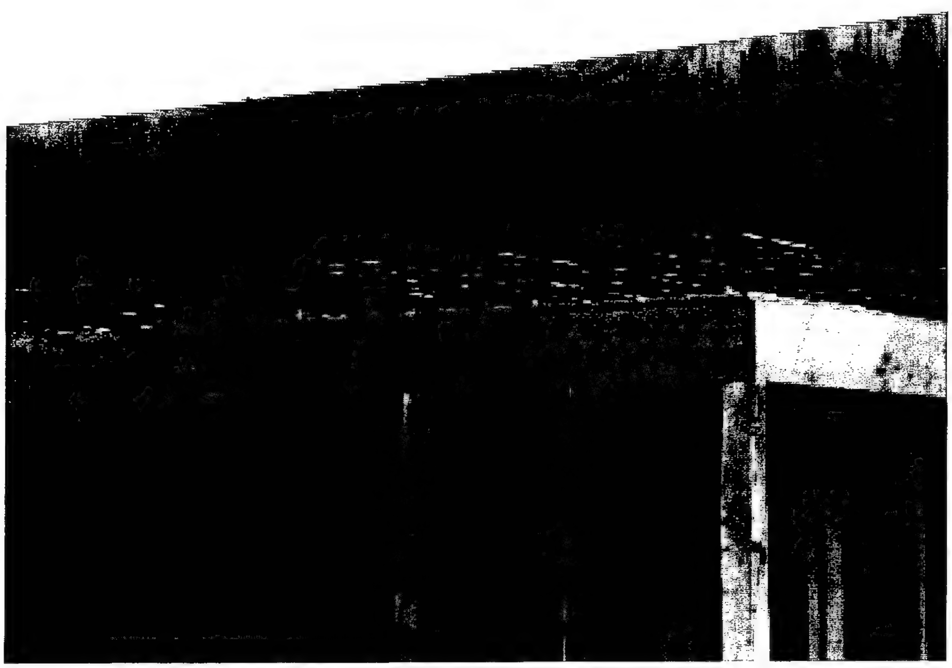

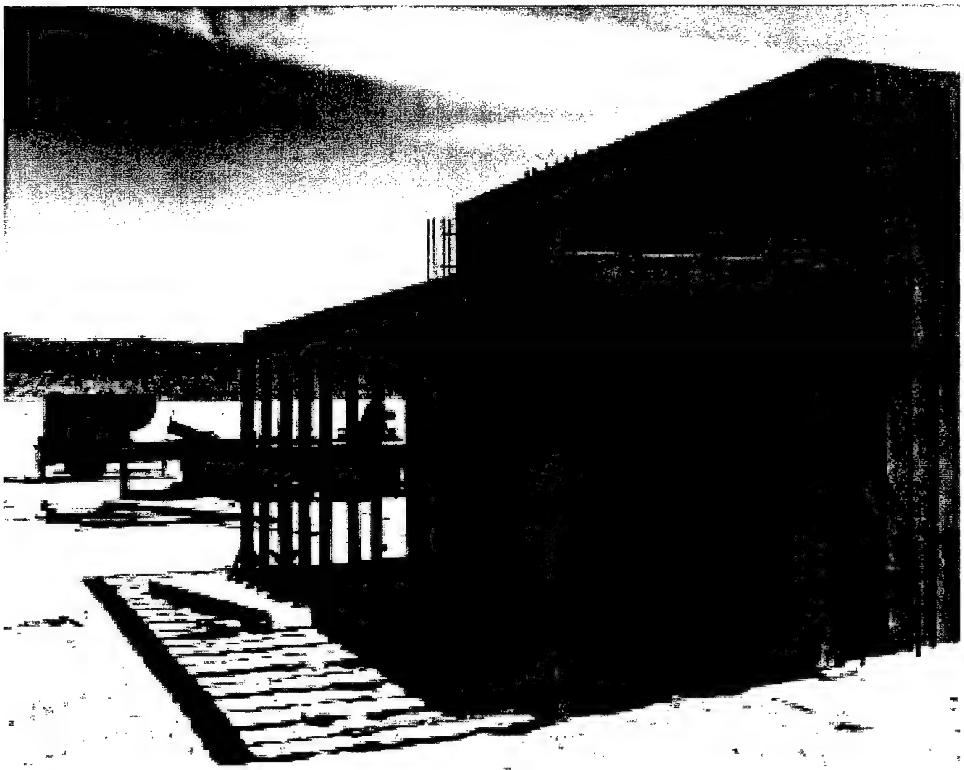

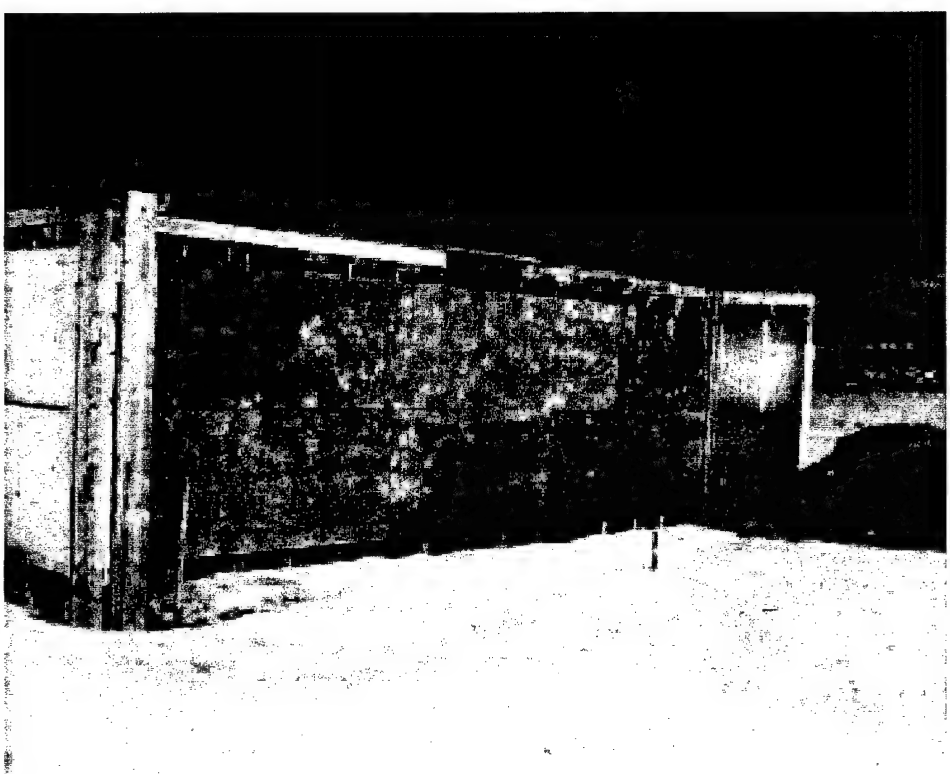

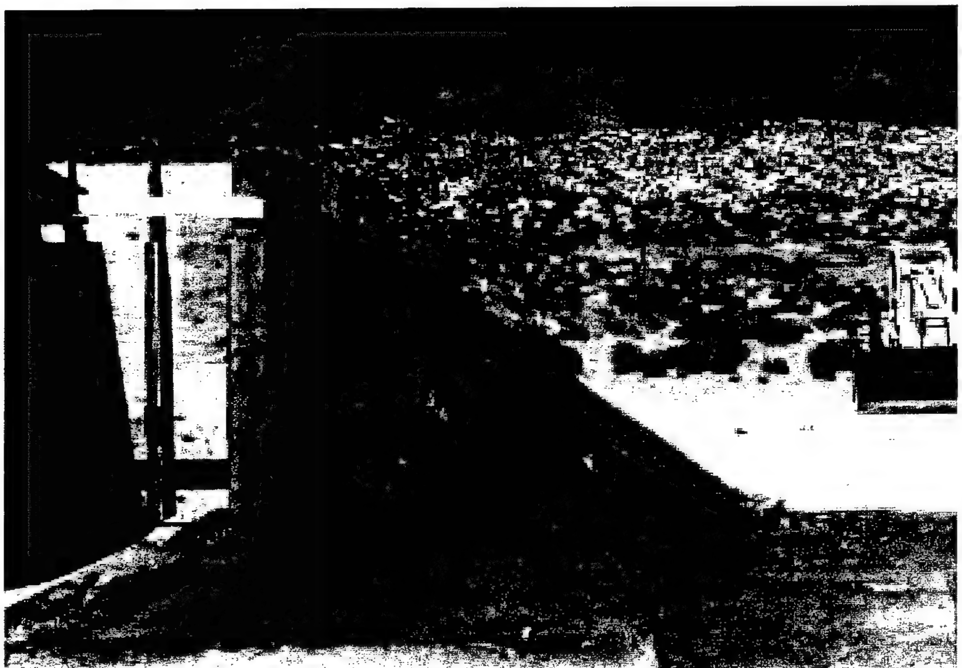

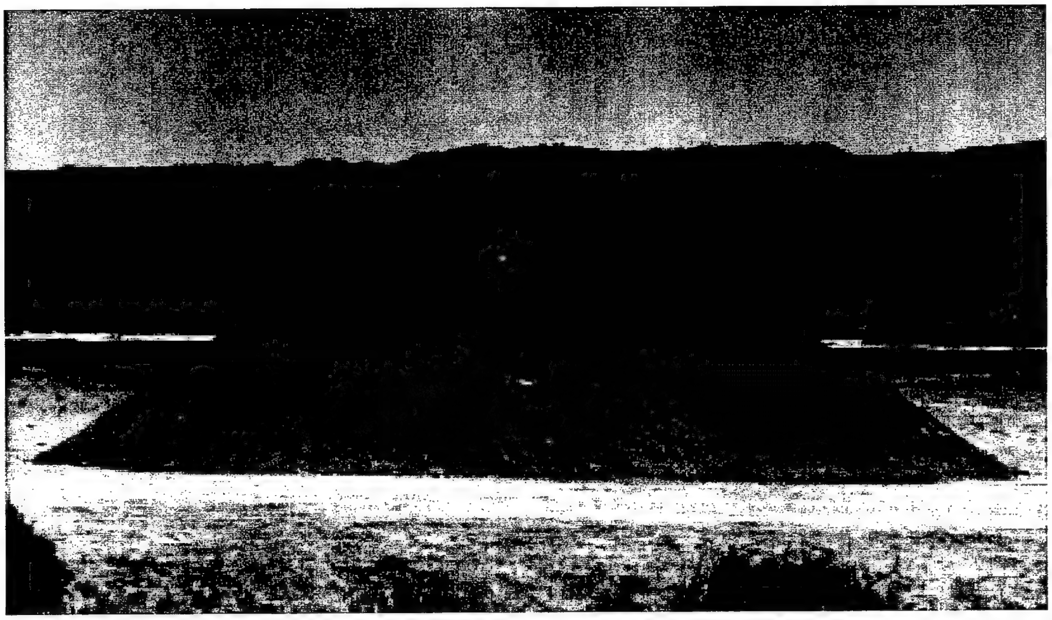

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Appendix B

DEBRIS LOCATIONS

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Description[a]	Range (ft)	Azimuth[b]		
		(deg)	(min)	(s)
Cartridge case piece	16.98	322	50	45
Cartridge case piece	24.1	22	40	25
Cartridge case piece	26.16	38	41	20
Cartridge case piece	26.35	2	27	30
Cartridge case piece	29.06	328	23	55
Projectile Case piece	29.9	10	40	50
Cartridge case piece	34.82	4	1	55
Cartridge case piece	35.18	48	46	0
Cartridge case piece	38.09	353	33	0
Cartridge case piece	42	37	19	40
Cartridge case piece	47.77	316	54	5
Cartridge case piece	50.05	282	47	0
Cartridge case piece	53.43	2	43	15
Cartridge case piece	65.6	40	10	0
Cartridge case piece	65.75	40	8	20
Cartridge case piece	65.92	39	8	0
Cartridge case piece	67.31	24	16	50
Cartridge case piece	80.3	14	42	0
Cartridge case piece	80.34	14	41	50
Cartridge case piece	80.42	27	5	45
Cartridge case piece	87.93	357	1	50
Cartridge case piece	94.99	87	23	35
Cartridge case piece	99.7	345	39	0
Cartridge case piece	99.78	345	39	35
Cartridge case piece	114.7	102	53	0
Cartridge case piece	156.83	306	30	50
Cartridge case piece	180.39	323	51	30
Cartridge case piece	191.99	350	57	55
Cartridge case piece	211.64	42	31	20
Cartridge case piece	218.98	153	17	25
Cartridge case piece	244.65	25	23	45
Cartridge case piece	248.55	270	0	55
Cartridge case piece	262.69	276	2	15
Cartridge case piece	290.7	299	33	0
Cartridge case piece	313.37	51	18	40
Cartridge case piece	318.19	5	19	5
Projectile case piece	15.25	12	3	0
Projectile case piece	17.59	314	2	0
Projectile case piece	18.66	99	44	5
Projectile case piece	20.03	123	49	55
Projectile case piece	22.9	38	29	10
Projectile case piece	25.96	145	0	20
Projectile case piece	27.05	281	21	5
Projectile case piece	29.33	344	57	35
Projectile case piece	29.56	275	7	10
Projectile case piece	38	292	50	0
Projectile case piece	38.05	353	33	30
Projectile case piece	40.86	42	50	35
Projectile case piece	50	282	30	15

See footnotes at end of table.

Description[a]	Range (ft)	Azimuth[b]		
		(deg)	(min)	(s)
Projectile case piece	50.14	142	23	45
Projectile case piece	55.89	19	3	10
Projectile case piece	66.42	17	48	20
Projectile case piece	126.91	7	7	5
Projectile case piece	150.12	304	44	5
Projectile case piece	218.9	354	15	40
Projectile case piece	233.56	49	16	50
Projectile case piece	669.95	264	52	50
Intact projectile (empty)	14.53	356	51	10
Intact projectile (empty)	17.17	27	55	0
Intact projectile (empty)	29.44	28	13	20
Intact projectile (empty)	59.49	28	46	40
Intact projectile (empty)	106.39	352	25	45
Intact projectile (live)	15.3	23	3	0
Intact projectile (live)	29.88	18	22	30
Intact projectile (live)	32.77	86	44	35
Intact projectile (live)	34.8	18	48	0
Intact projectile (live)	41.86	17	43	10
Intact projectile (live)	99.25	11	21	15
Intact projectile (live)	116.54	8	14	45
Intact projectile (live)	134.65	274	5	35
Intact projectile (live)	240.79	312	8	40

[a]Survey point is located on top of structure, 1.6 feet behind front wall.

[b]0 degrees is out the front of the structure.

Appendix C

INSTRUMENTATION RESULTS

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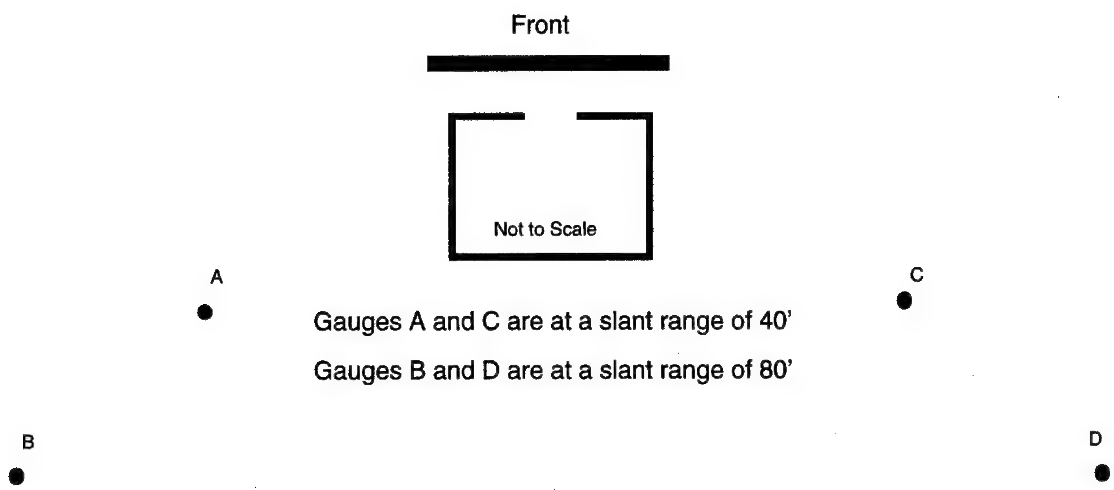


NOTE: No zero time sensor was deployed because it was assumed that all events would occur inside the structure

Figure C-1. Pressure Gauge Locations

Table C-I. On-Site Observations

Event	Elapsed time (h:m:s)	Observation	Event	Elapsed time (h:m:s)	Observation
1	0:00:00	Start	40	0:43:10	Pop
2	0:12:28	Pop	41	0:43:48	Pop
3	0:17:55	Pop	42	0:44:13	Pop
4	0:18:25	Pop	43	0:44:27	Pop
5	0:19:14	Pop	44	0:45:06	Boom
6	0:21:16	Pop	45	0:45:11	Boom
7	0:22:37	Boom	46	0:45:42	Pop
8	0:23:14	Pop	47	0:47:13	Boom
9	0:23:20	Pop	48	0:47:30	Boom
10	0:23:26	Pop	49	0:47:46	Boom
11	0:23:36	Pop	50	0:47:55	Boom
12	0:24:08	Pop	51	0:49:50	Pop
13	0:24:35	Pop	52	0:50:45	Boom
14	0:24:38	Pop	53	0:53:01	Boom
15	0:24:40	Pop	54	0:54:48	Boom
16	0:25:51	Pop	55	0:55:13	Pop
17	0:26:11	Boom	56	0:56:01	Pop
18	0:27:20	Pop	57	0:56:05	Boom
19	0:28:01	Pop	58	0:57:46	Boom
20	0:29:55	Pop	59	0:58:46	Boom
21	0:31:18	Pop	60	1:00:34	Pop
22	0:31:35	Boom	61	1:01:38	Pop
23	0:33:48	Pop	62	1:02:15	Pop
24	0:34:06	Boom	63	1:02:26	Boom
25	0:36:32	Boom	64	1:02:37	Boom
26	0:36:47	Pop	65	1:05:37	Boom
27	0:37:25	Pop	66	1:06:34	Boom
28	0:37:29	Pop	67	1:06:59	Boom
29	0:38:12	Pop	68	1:10:19	Boom
30	0:38:15	Pop	69	1:11:01	Boom
31	0:39:12	Pop	70	1:12:28	Pop
32	0:39:31	Boom	71	1:14:01	Pop
33	0:39:46	Boom	72	1:37:13	Boom
34	0:39:53	Pop	73	1:38:08	Boom
35	0:40:53	Boom	74	1:53:23	Boom
36	0:42:12	Pop	75	2:16:31	Boom
37	0:42:16	Boom	76	2:25:53	Boom
38	0:42:32	Boom	77	2:33:12	Boom
39	0:43:03	Pop			

Table C-II. Event Times

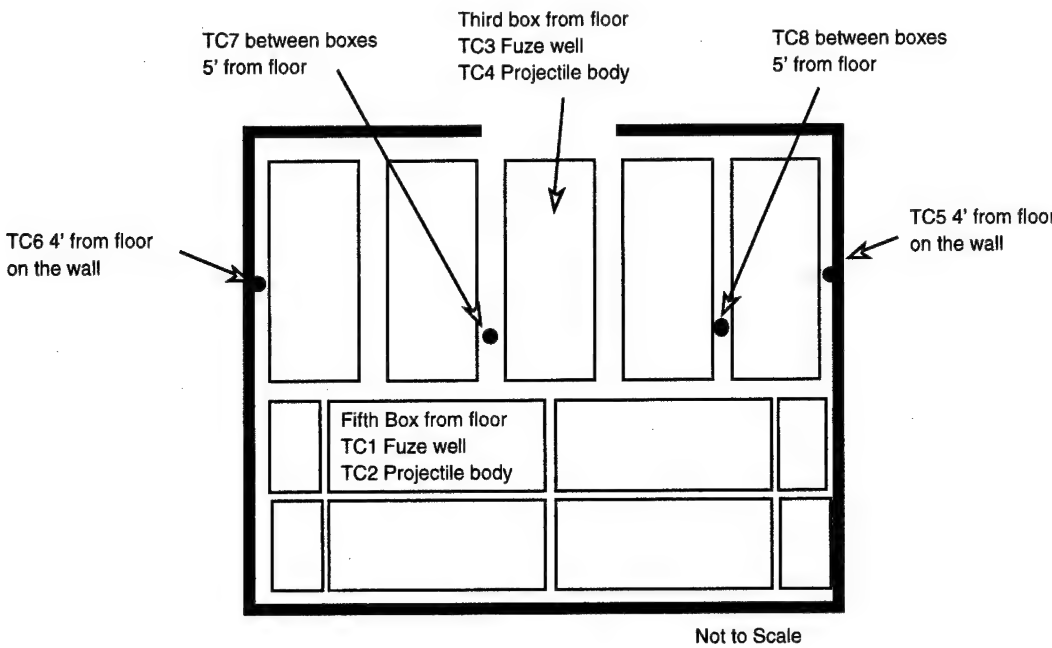
Digital event No.	Observer event No.	Time code (h:m:s)	Observer event time (h:m:s)	Elapsed time (h:m:s)[a]	
				Time code	Observer
	Fire start	10:06:14.14	10:05:15	—	—
1	7	10:28:51.05	10:27:52	0:22:37.05	0:22:37
2	17	10:32:25.09	10:31:26	0:26:11.09	0:26:11
3	22	10:37:44.72	10:36:50	0:31:30.72	0:31:35
4	24	10:40:19.39	10:39:21	0:34:05.39	0:34:06
5	25	10:42:46.08	10:41:47	0:36:32.08	0:36:32
6	32	10:45:45.95	10:44:46	0:39:31.95	0:39:31
7	33	10:46:00.48	10:45:01	0:39:46.48	0:39:46
8	35	10:47:07.89	10:46:08	0:40:53.89	0:40:53
9	37	10:48:30.06	10:47:31	0:42:16.06	0:42:16
10	38	10:48:46.39	10:47:47	0:42:32.39	0:42:32
11	42	10:50:26.76	—	0:44:12.76	—
12	44	10:51:20.10	10:50:21	0:45:06.10	0:45:06
13	45	10:51:25.00	10:50:26	0:45:11.00	0:45:11
14	46	10:51:52.00	—	0:45:38.00	—
15	47	10:53:27.70	10:52:28	0:47:13.70	0:47:13
16	48	10:53:41.71	10:52:45	0:47:27.71	0:47:30
17	49	10:54:00.61	10:53:01	0:47:46.61	0:47:46
18	—	10:54:01.00	—	0:47:47.00	—
19	50	10:54:09.58	10:53:10	0:47:55.58	0:47:55
20	52	10:56:58.29	12:56:00	0:50:44.29	2:50:45
21	53	10:59:15.16	10:58:16	0:53:01.16	0:53:01
22	54	11:00:41.63	11:00:03	0:54:27.63	0:54:48
23	55	11:01:23.03	—	0:55:09.03	—
24	56	11:02:18.26	11:01:20	0:56:04.26	0:56:05
25	58	11:03:59.86	11:03:01	0:57:45.86	0:57:46
26	59	11:04:59.69	11:04:01	0:58:45.69	0:58:46
27	60	11:06:47.56	—	1:00:33.56	—
28	61	11:07:49.01	—	1:01:35.01	—
29	63	11:08:40.39	11:07:41	1:02:26.39	1:02:26
30	—	11:08:41.67	—	1:02:27.67	—
31	64	11:08:51.33	11:07:52	1:02:37.33	1:02:37
32	65	11:11:52.41	11:10:52	1:05:38.41	1:05:37
—	66	—	11:11:49	—	1:06:34
33	67	11:13:11.81	11:12:14	1:06:57.81	1:06:59
34	68	11:16:33.80	11:15:34	1:10:19.80	1:10:19
35	69	11:17:16.58	11:16:16	1:11:02.58	1:11:01
36	72	11:43:27.68	11:42:28	1:37:13.68	1:37:13
37	73	11:44:23.11	11:43:23	1:38:09.11	1:38:08
—	74	—	11:58:38	—	1:53:23
—	75	—	12:21:46	—	2:16:31
—	76	—	12:31:08	—	2:25:53
—	77	—	12:38:27	—	2:33:12

[a]Elasped times are measured relative to the fire start time.

Table C-III. Airblast Data

Digital event No.	Pressure (psi)				Arrival time (ms)[a]			
	Gauge A	Gauge B	Gauge C	Gauge D	Gauge A	Gauge B	Gauge C	Gauge D
1	0.34	0.17	—	—	22.6	39.8	—	—
2	2.05	0.98	—	—	23.0	40.0	—	—
3	2.27	1.05	—	—	23.6	40.0	—	—
4	2.79	1.14	—	—	31.7	40.0	—	—
5	0.79	0.39	—	—	31.5	39.8	—	—
6	1.12	0.56	—	—	23.0	40.0	—	—
7	1.35	0.60	—	—	23.5	40.0	—	—
8	0.67	0.43	—	—	23.0	40.0	—	—
9	1.49	0.74	—	—	23.1	40.0	—	—
10	0.36	1.52	—	—	23.9	40.0	—	—
11	0.30	0.16	—	—	23.6	40.0	—	—63.6
12	0.65	0.37	—	—	—	—	—	—
13	0.02	0.02	—	—	—	—	—	—
14	—	0.10	—	—	—	40.0	—	—
15	1.36	0.91	—	—	23.4	40.0	—	—
16	0.91	0.61	—	—	23.1	40.0	—	—
17	1.07	0.64	—	—	23.6	40.0	—	—
18	0.10	0.02	—	—	22.5	40.0	—	—
19	0.53	0.28	—	—	23.3	40.0	—	—
20	—	0.56	—	—	—	40.0	—	—
21	—	0.64	—	—	—	40.0	—	—
22	0.65	0.38	—	—	23.2	40.0	—	—
23	0.08	0.03	—	0.02	24.4	40.0	—	42.8
24	0.65	0.38	—	0.38	23.2	40.0	—	43.3
25	1.06	0.62	—	—	23.1	40.0	—	—
26	0.80	0.63	—	—	22.5	39.9	—	—
27	0.08	0.06	—	0.02	22.5	39.6	—	38.5
28	0.09	0.08	—	0.10	22.7	40.0	—	42.0
29	1.14	0.91	—	—	22.6	40.0	—	—
30	0.05	0.04	—	—	29.0	40.0	—	—
31	1.40	1.01	—	0.80	23.1	40.0	—	42.5
32	2.33	1.45	—	0.88	23.0	40.0	—	42.6
33	0.22	0.13	—	0.13	22.6	40.0	—	41.9
34	2.84	1.80	—	0.15	23.0	40.0	—	41.4
35	1.92	1.24	—	0.21	23.1	40.0	—	39.8
36	2.35	1.59	—	1.52	22.9	40.0	—	40.9
37	0.77	0.52	—	0.91	22.6	40.0	—	40.3

[a]Arrival times are referenced to 40 ms before Gauge B (no zero time).



Top view

Figure C-2. Thermocouple Locations

Table C-IV. Thermocouple Results

Thermocouple No.	Position	Maximum temperature (°C)	Record duration (min)
1	Fuze well	26	21.8
2	Projectile exterior	29	21.8
3	Fuze well	25	21.8
4	Projectile exterior	59	21.8
5	Magazine wall	750	21.8
6	Magazine wall	710	7
7	Flame	1300	21.8
8	Flame	1180	16

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Appendix D

THERMAL ANALYSIS

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5 May 97

MEMORANDUM

From: Rodney M. Harris, Aeromechanics & Thermal Analysis Section (Code 473110D)
To: Michael M. Swisdak, Jr., Explosive Technology Application Division, Code 950
Via: Head, Aeromechanics & Thermal Analysis Section (Code 473110D) *W*

Subj: THERMAL ANALYSIS OF THE RED RIVER IGLOO FIRE AND CHINA LAKE MINI-MAGAZINE FIRE TEST

Ref: (a) CFAST, the Consolidated Model of Fire Growth and Smoke Transport, R. D. Peacock, *et al*, NIST Technical Note 1299, 1992
(b) National Institute of Standards and Technology. A Programmer's Reference Manual for CFAST, the Unified Model of Fire Growth and Smoke Transport , W. W. Jones and G. P. Forney, NIST 1283, 1990
(c) "Responses of Concrete Walls to Fire", C.L.D. Huang, *et al*, *International Journal of Heat and Mass Transfer*, Vol. 34, No. 3. 1991
(d) *Fire Protection Handbook*, 16/e. National Fire Protection Association
(e) W. W. Jones. "Modeling Smoke Movement through Compartmented Structures", *J. of Fire Sciences*, v. 11, pp. 172-183, March/April 1993
(f) Network Analysis Associates. SINDA 1987/ANSI Manual, 21 October 1987, Fountain Valley, CA
(g) PDA Engineering. PATRAN User's Guide, Release 2.4, September 1989, Costa Mesa, CA
(h) Drawing package, Mini Magazine, Concrete Earth-Covered; U. S. Army Engineer Division, Huntsville

Encl: (1) Figures 1 through 17

1. Background. The Red River igloo accident on 21 August 1996 involved a 48-hour fire in a 28-ft by 60-ft concrete cylindrical arch igloo which caused enough heat damage to result in the roof's collapse (see Figure 1). A chief concern from this accident was that if some munitions within the magazine reacted after the structure was damaged, the debris dispersal from the blast could exceed the safety limits of the damaged structure. A Miniature Magazine was tested on 26 June 1996 at China Lake. The magazine had storage chamber dimensions of 7 ft wide by 8 ft deep by 7 ft tall and a wall thickness of 1 ft reinforced concrete. The magazine was loaded with four pallets (120 rounds / 60 wood boxes) of 105 mm ammunition and ignited with 10 gal of gasoline. The fire lasted about two hours and eroded about 3 to 4 inches of the concrete walls and roof. The Explosive Technology Application Division (Code 950T) at Indian Head asked the Aeromechanics and Thermal Analysis Section (Code 473110D) at China Lake to use the controlled data from the Miniature Magazine test to create a model of the effects of the fire on the concrete walls and then to apply that model to the Red River igloo accident.

2. Analysis Approach. The problem was divided into two parts: determining the heat generation and gas (smoke) transport from the fire and determining the amount of heat that is absorbed by the walls, floor, and roof of the structures.

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a. Fire Model. The fire was modeled by determining the total amount of energy released from the fuel and the spread and venting of the hot gas byproducts (smoke). These calculations were performed using the Consolidated Fire And Smoke Transport (CFAST) code (see References (a) and (b)). CFAST is a zone model that predicts the thermal environment in a compartment fire. A zone model divides the volumes in each chamber into two layers, each of which are assumed to be internally uniform, and provides for their interactions. The upper layer is assumed to contain the hot combustion products and the lower layer is assumed to contain the ambient air. CFAST is based on solving a set of ordinary differential equations that predict the change in the enthalpy and mass over time. The equations are derived from the conservation equations for energy, mass, momentum, and an equation of state (ideal gas law). These equations are rearranged to form a set of predictive equations for the sensible variables in each compartment. The code uses venting to adjust flow to maintain constant pressure by calculating the venting from chamber to chamber and to the external environment. Both the mini-magazine and the Red River igloo consisted of one chamber with venting to the outside.

b. Heat Absorption. The heat absorbed by the roof and walls was calculated by a computer model of the convection and radiation from the hot gasses to the surface and conduction through the thickness. First, a 3-D finite element model of a symmetric segment of the wall of the mini-magazine was constructed which included the steel re-bar pattern (see Figure 2). The model was constructed using PATRAN which was then converted to a finite difference SINDA model for computation. It was found that the steel re-enforcement had little effect in three dimensions so only 2-D models were used for the Red River igloo. Figure 3 shows the grid used for the roof section of the igloo and Figure 4 shows the grid for the lower wall section. The SINDA model calculated the heat transfer due to convection and radiation from the fire to the surface and then the conduction through the steel and concrete. The model included an artificial spalling that removed surface nodes as they reached a set temperature.

c. Boundary Conditions and Assumptions.

1) The most influencing assumption is the rate at which the fuel is consumed. To calculate the fire temperature conditions, the CFAST code required the total energy content of the fuel and the time the fire took to consume it. The mini-magazine contained 4 wood pallets, 60 wood boxes, 120 rounds of 105 mm ammunition and 10 gallons of gasoline. The energy contents were as follows:

Fuel	Weight	Energy Content
Wood	1814.4 kg	21.0 MJ/kg
Comp B HE	250.4 kg	48.03 kJ/kg
M1 Propellant	152.4 kg	2.257 MJ/kg
Gasoline	37.6 kg	46.8 MJ/kg

A weighted average for the total amount of energy for the mini-magazine was thus 17.837 MJ/kg. The mini-magazine fire was assumed to burn all of the fuel in a 60 minute time frame.

2) The Red River igloo contained 2,840 boxes of 105 mm ammunition on 125 wood pallets, 43,376 M10 propellant charges, 5,012 M9 propellant charges, and 1,593 black powder charges. The energy contents were as follows:

Fuel	Weight	Energy Content
Wood	84,052 kg	21.0 MJ/kg
Comp B HE	11,854 kg	48.03 kJ/kg
M1 Propellant	7,215 kg	2.257 MJ/kg
M10 Propellant	2,597 kg	2.533 MJ/kg
M9 Propellant	17 kg	2.119 MJ/kg
Black Powder	29 kg	11.29 MJ/kg

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A weighted average for the total amount of energy for the mini-magazine was thus 16.914 MJ/kg. The Red River fire was assumed to burn all of the fuel in a 48 hour time frame.

3) The spalling temperature was estimated from information in References (c) and (d). Assumptions had to be made as to the moisture content in the concrete. The moisture content is a major contributor to concrete spalling. The concrete in the mini-magazine was less than a month old at the time of the fire test while the concrete in the Red River Igloo was over 40 years old. It was assumed that the moist concrete in the mini-magazine would spall at 1000°F and the Red River concrete would spall at 1200°F. Upon examining the results, it was seen that a spalling temperature of 1200°F for older concrete was much too low and a value of 1700°F was then used.

4) The fire and hot gases (smoke) were assumed to occupy an upper layer within the magazines so that only the roof and walls would be exposed to convective heating. The ash layer on the floor protected it from the severe heat of the fire. The convection rate to the walls and roof was assumed to be 4 Btu/ft^{2}hr°F, the radiation viewfactor from the fire/smoke was assumed to be unity, and the emisivity of the blackened walls was assumed to be 0.9.

5) Note that the fire in the mini-magazine is assumed to have burned more evenly than the fire in the much larger Red River igloo. Some areas within the igloo would have burned more intensely during the consumption of the energetic material and less intensely while burning the wood pallets and boxes. To facilitate computation, it was assumed that the fires were evenly spread and burned at a constant rate.

3. Results. The results are in two parts; first, the output from the CFAST code predicted the gas temperatures from the fire; then, the fire temperatures were used as input to the SINDA code to predict the temperatures in the concrete.

a. Mini-magazine.

1) The calculated temperatures of the upper gas layer in the mini-magazine fire are shown in Figure 5. The upper gas layer was calculated by CFAST to extend down to about 2 feet above the floor, thus the roof and most of the walls were exposed to temperatures of 1400°F at the start of the fire and 1900°F at the end of the fire. The temperatures of the upper layer were applied as a convective and radiative boundary condition to the concrete surface to determine the temperature response. Figure 6 shows the temperature contours in a 3-D segment of the wall at the point of maximum heating at the end of the fire (60 minutes) when no erosion was assumed. In Figure 7, erosion (heat spalling) is assumed to occur when the concrete reached 1000°F. Here, the heat penetrates twice as far as in the no erosion case. In the erosion case, the model simulates erosion by changing the conductivity and specific heat of all nodes that attain 1000°F or more, thus effectively removing them from the calculation. By comparing the heat penetration of all nodes above 1000°F (considered removed) to the reinforcement bar pattern in Figure 2, it can be seen that the concrete surface is predicted to erode just past the vertical bar (about 4 inches from the original surface). Figure 8 shows a picture of the erosion damage to the walls and ceiling in the interior of the mini-magazine after the fire. The erosion can be seen to penetrate about 4 inches on the walls and ceiling.

2) Figures 9 and 10 show external views of the mini-magazine after the fire. During the test, the flames and smoke were observed to exit the door, wrap around the cantilevered roof and downwind of the door (to the right in the pictures). The lip of the cantilevered roof and the downwind wall show more heat damage than the upwind wall.

b. Red River Igloo.

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1) The calculated temperatures of the upper gas layer and a mid-level gas layer in the igloo fire are shown in Figure 11. The upper gas layer was calculated by CFAST to extend down to about 1 foot above the floor. The layer thickness is not accurately calculated because the CFAST code assumes a flat roof and the Red River Igloo was an arched roof. Also, due to the curved roof and the larger dimensions, the variation in the CFAST predicted temperatures within the layer would be greater than for the mini-magazine. To adjust for the temperature variations in the layer, a mid-layer gas was assumed to be 20% lower. The upper layer temperatures in Figure 11 show a jump to 1000°F within the first hour with a steady climb to 2250°F in the first 12 hours. Between 12 and 18 hours, the smoke layer has reached a steady-state temperature of about 2300°F which is maintained until the fire goes out at 48 hours. The mid-layer gas reaches a steady state of about 1850°F between 12 and 18 hours. The model does not account for the collapse of the roof during the latter half of the fire which would allow for more venting and thus lower temperatures afterwards.

2) Figure 12 shows the temperatures of a 2-D cross section of a segment of the Red River igloo roof and soil cover at 12 hours into the fire. In this case, the spalling temperature was first assumed to be 1200°F which indicates that all of the concrete of the roof structure has eroded away in the first 12 hours. Observations during the fire indicated that the roof did not collapse until after 24 to 36 hours. To adjust the analysis, a higher spalling temperature of 1700°F (to reflect the older dryer condition of the concrete) was chosen. Figure 13 shows the predicted temperatures of the roof section at 7 hours with the higher spalling temperature. This color graph indicates that two to three inches have spalled away by this time. It can also be seen by the lateral oscillatory temperature response that an instability in the model has set in. This instability is due to the artificial spalling and the extreme temperature load and only occurred when the input temperature exceeded 2000°F and the spalling temperature was set at 1700°F. Because of the instability, no results were calculated beyond seven hours for these conditions.

3) Figures 14 through 16 show the temperatures of a 2-D cross section of a segment of the lower wall and soil cover at 12, 24, and 48 hours into the fire. In this case, the spalling temperature was assumed to be 1700°F. Due to the curved structure, the temperatures applied to the lower wall were assumed to be 20% lower than the upper layer temperatures predicted by CFAST. Figure 14 shows that at 12 hours only the surface of the wall reaches temperatures above the assumed spalling temperature. Figure 16 shows that the spalling temperatures would only penetrate a few inches at most even after 48 hours. Note that after the roof collapsed the temperatures within the igloo would be reduced.

4) Figure 17 shows the inside of the igloo after the fire during clean up. Most of the lower wall shows little heat spalling damage while the roof structure has collapsed. The temperature of the steel reinforcement bars in the roof section were calculated to reach at least 1500°F in 7 hours which would reduce the steel's strength to below 20%. Once the erosion of the roof concrete reached the soil cover, the roof could collapse.

4. Conclusions.

a. The temperature of enclosed fires can be reasonably calculated using the CFAST code. The most influencing assumption about the input conditions is the rate at which the fuel is consumed. For smaller fires under controlled conditions, such as the mini-magazine, the duration of the fire and the amount of fuel can be used to calculate a burn rate and total energy production. Also, due to the small confinement, the fuel can be assumed to burn evenly. For larger fires, the intensity of the burn would vary in different regions of the fire area, i.e., for the Red River accident the fire would spread from pallet to pallet in various stages and rates. The most efficacious analysis would assume a burn rate that would consume the total fuel volume within the approximate burn time. Thus, the predicted temperatures for the Red River igloo represent the best information, absent

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measured temperatures, and provide reasonable input data for calculating the damage to the structure.

b. The spalling damage to concrete is highly dependent on the moisture content and heat input. Lacking any exact data on the moisture content for the two magazines studied, assumptions were made as to the spalling temperatures. The spalling temperature chosen for the mini-magazine produced results that agreed with the outcome of the fire test. The predicted erosion shown in Figure 7 closely matched the actual erosion seen in Figure 8. A much higher spalling temperature had to be assumed for the older (dryer) concrete in the Red River igloo. The model predicted that little spalling would occur on the side walls (Figure 15) and much more would occur at the roof (Figure 13). The temperature of the steel in the roof section may have reached values over 2000°F before the roof collapsed. No effort was made to correct the instability of the model (due to the artificial spalling) that occurred during the most severe input conditions at the roof section as the effort would beyond the scope of the task. The data generated to the seven hour point were sufficient to demonstrate more severe structural damage occurred at the roof section than at the lower walls. The predictions of the model show good general agreement with actual outcome of the fire shown by the picture of the inside of the igloo after the fire (Figure 17).

5. Future Work.

a. In order to use thermal models to predict magazine performance in fire scenarios *a priori*, a better database of spalling effects needs to be gathered. The spalling portions of the models used in this study were adjusted to match the observed results. Without accurate spalling information, the models would underpredict heat penetration, and thus structural integrity.

b. To protect concrete magazines from heat spalling damage during fires, a study could be done to determine effective insulation techniques that could be inexpensively applied for thermal protection. If it is assumed that once a fire starts in a magazine, the fire will burn to completion, then the goal should be to protect the structure long enough to maintain adequate structural integrity to mitigate blast and debris damage to its surroundings. The insulation protection could be used to retrofit only existing magazines shown to be susceptible to failure.

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Enclosure 1
(Figures 1 through 17)

Figure 1. External View of Red River Igloo After The Fire.

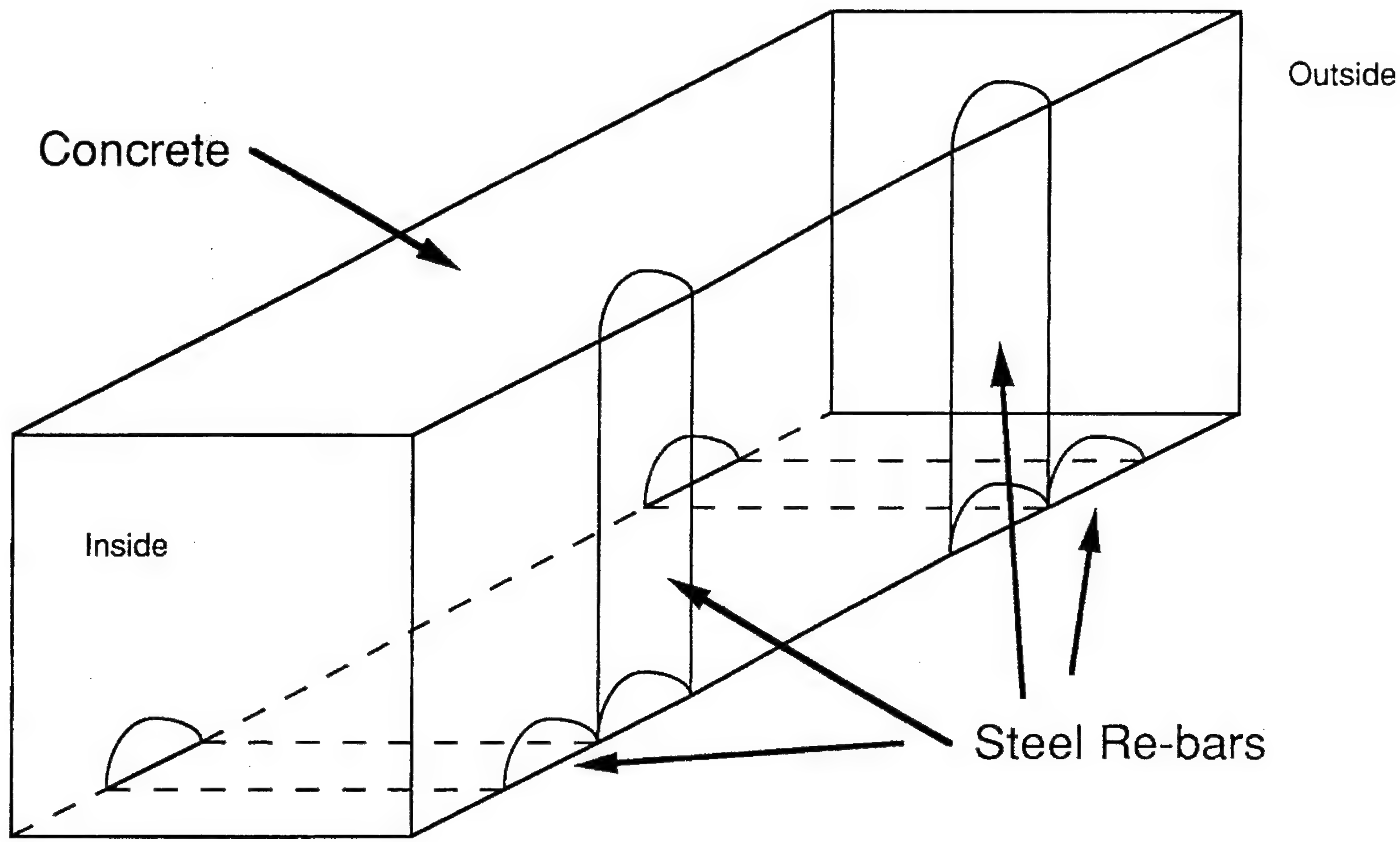

Figure 2. Symmetric Wall Segment With Re-bar Patern.

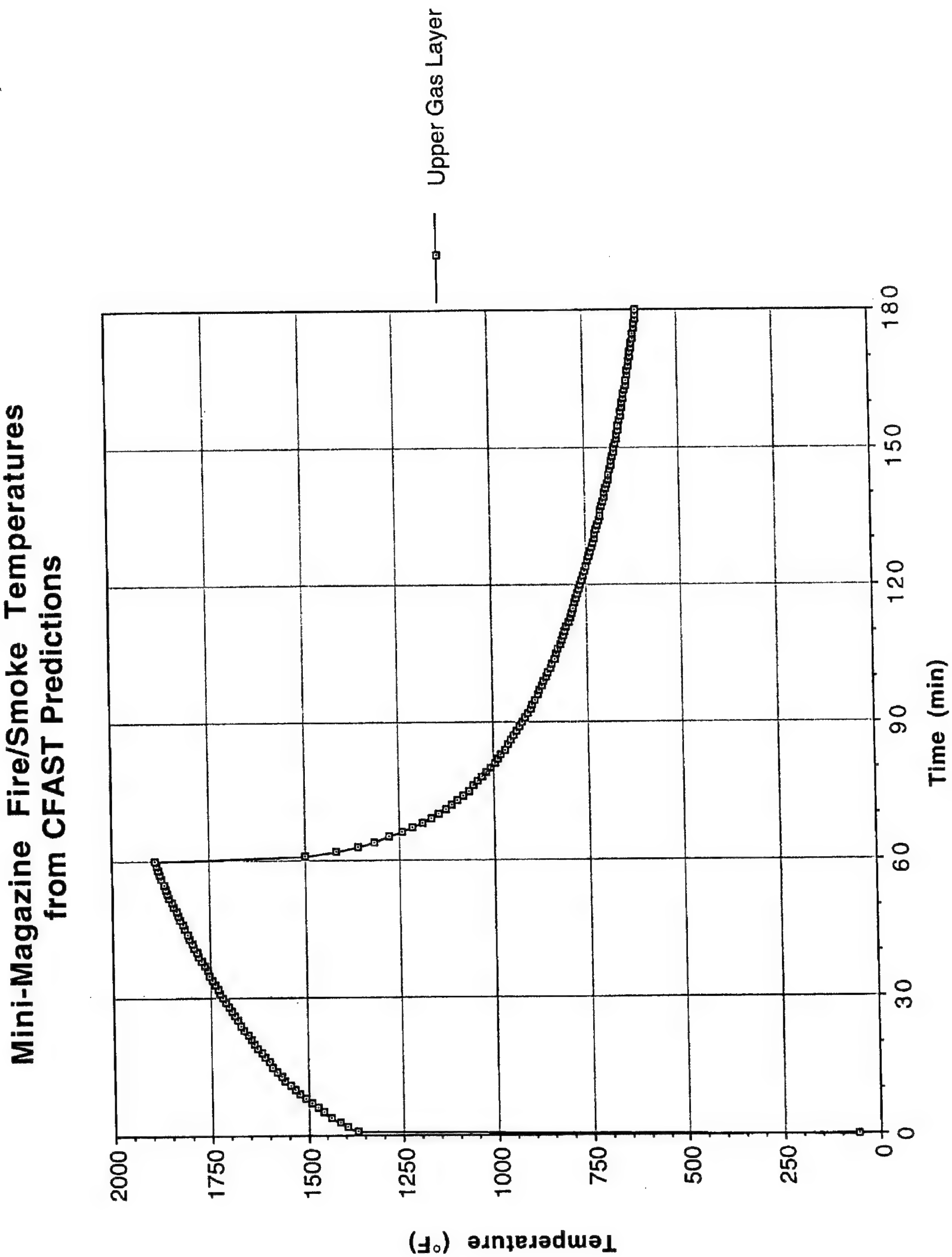

Figure 5. Mini-Magazine Temperatures.

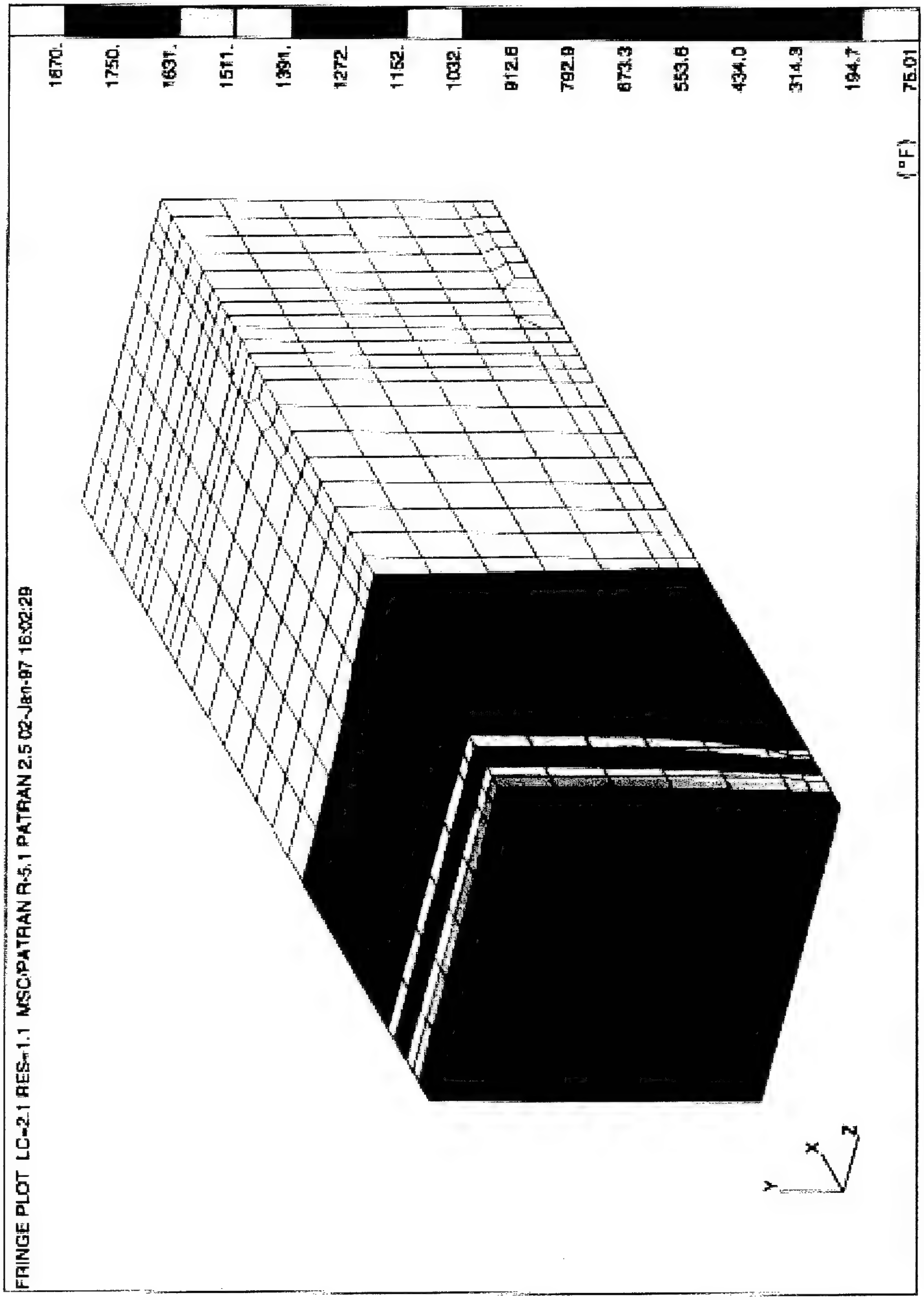

Figure 6. Mini-Magazine Wall Segment - No Erosion

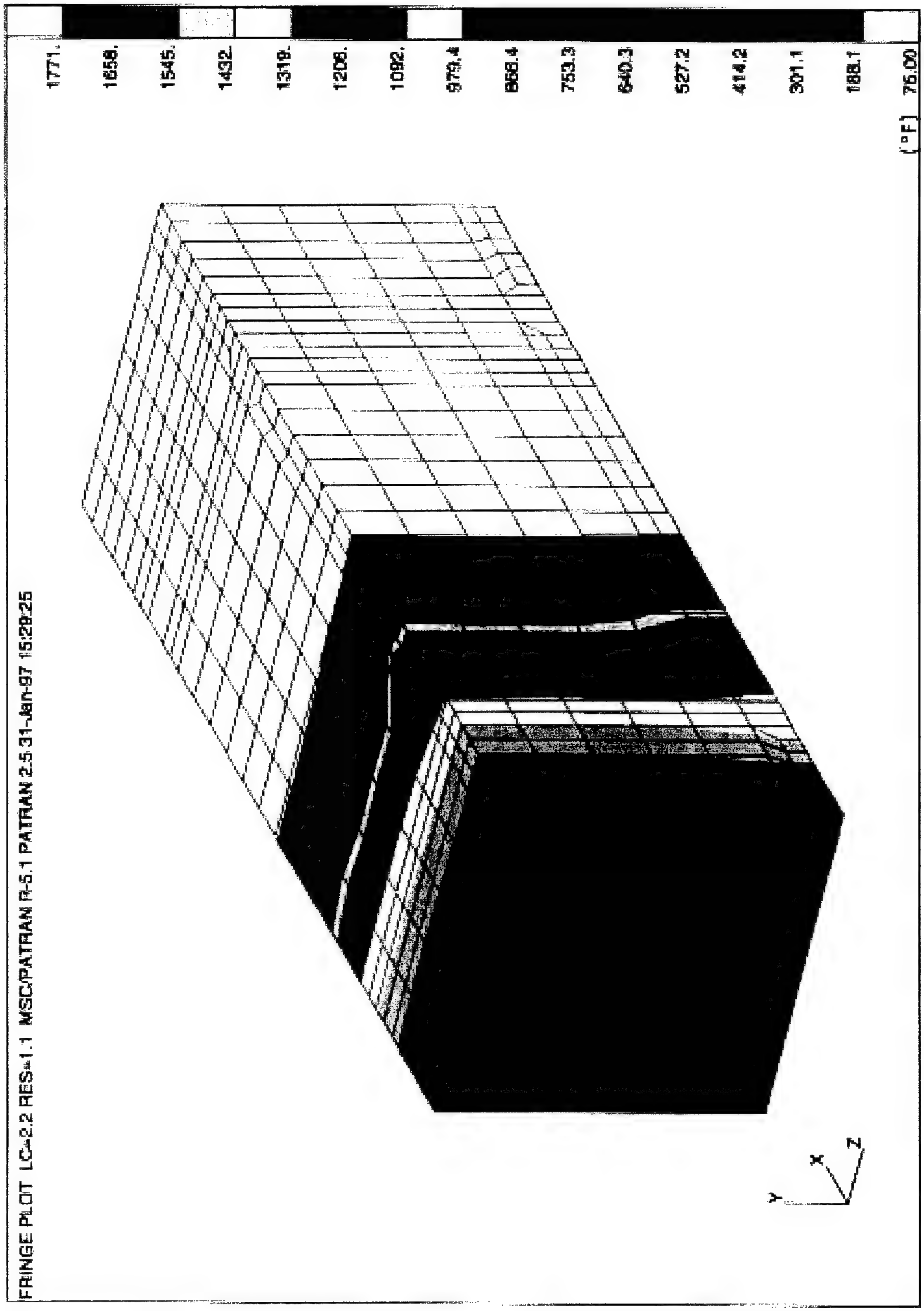

Figure 7. Mini-Magazine Wall Segment- With Erosion

Figure 8. Mini-Magazine Fire Erosion Damage.

Figure 9. External View of Mini-Magazine After The Fire.

Figure 10. Damage To Roof and Wall of Mini-Magazine.

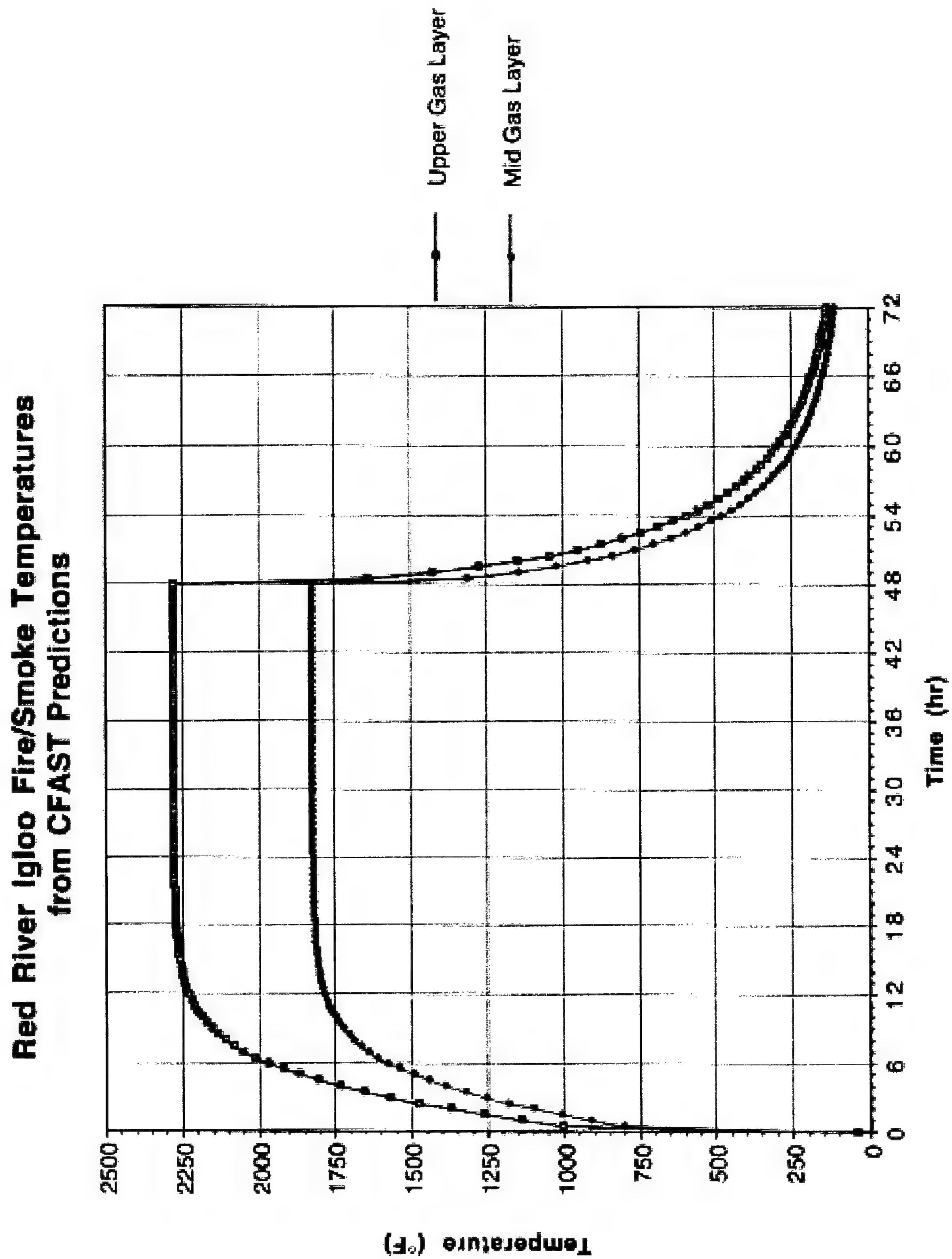

Figure 11. Red River Igloo Temperatures.

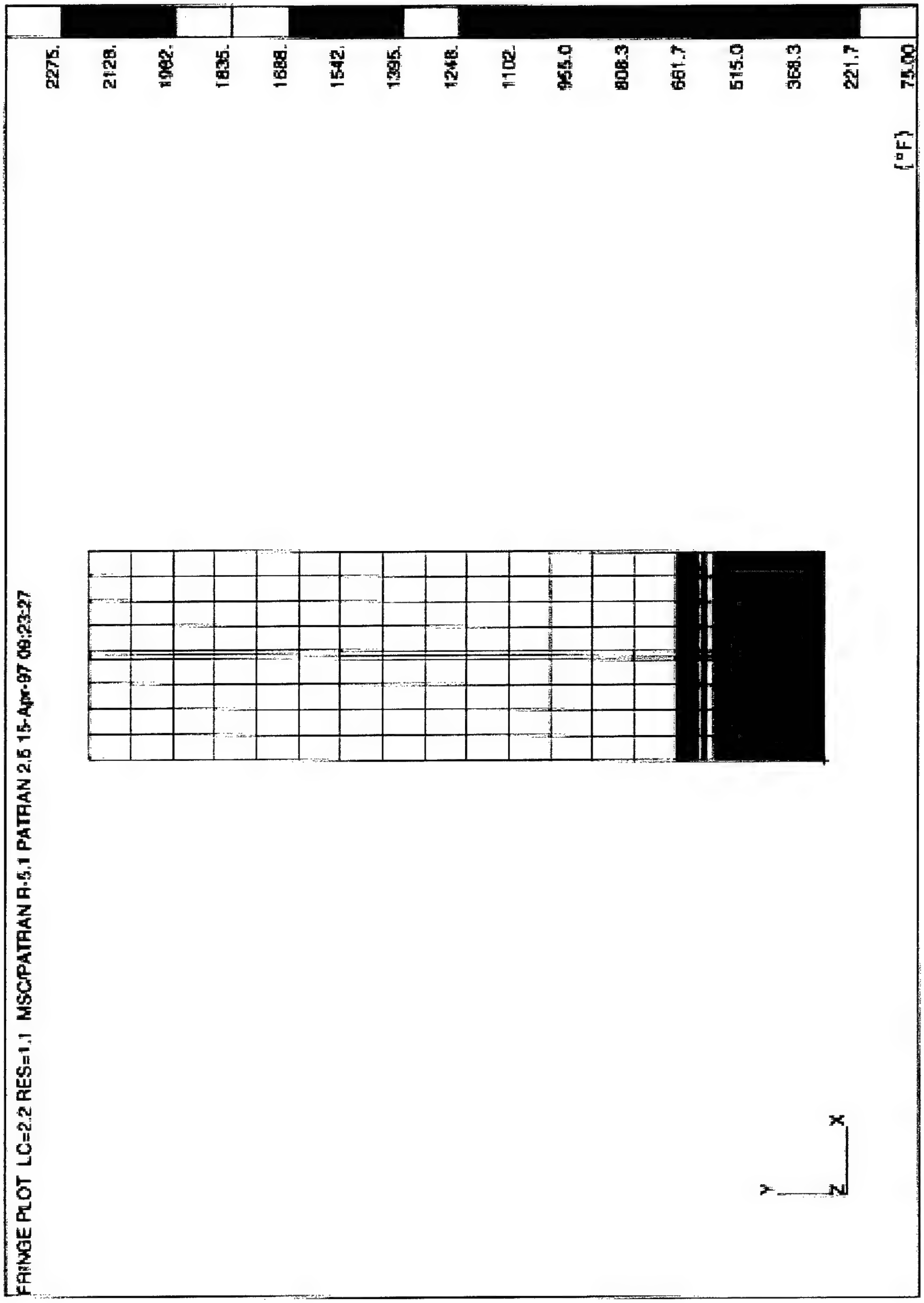

Figure 12. Red River Igloo Roof at 12 hr. Spalling Temp. 1200°F

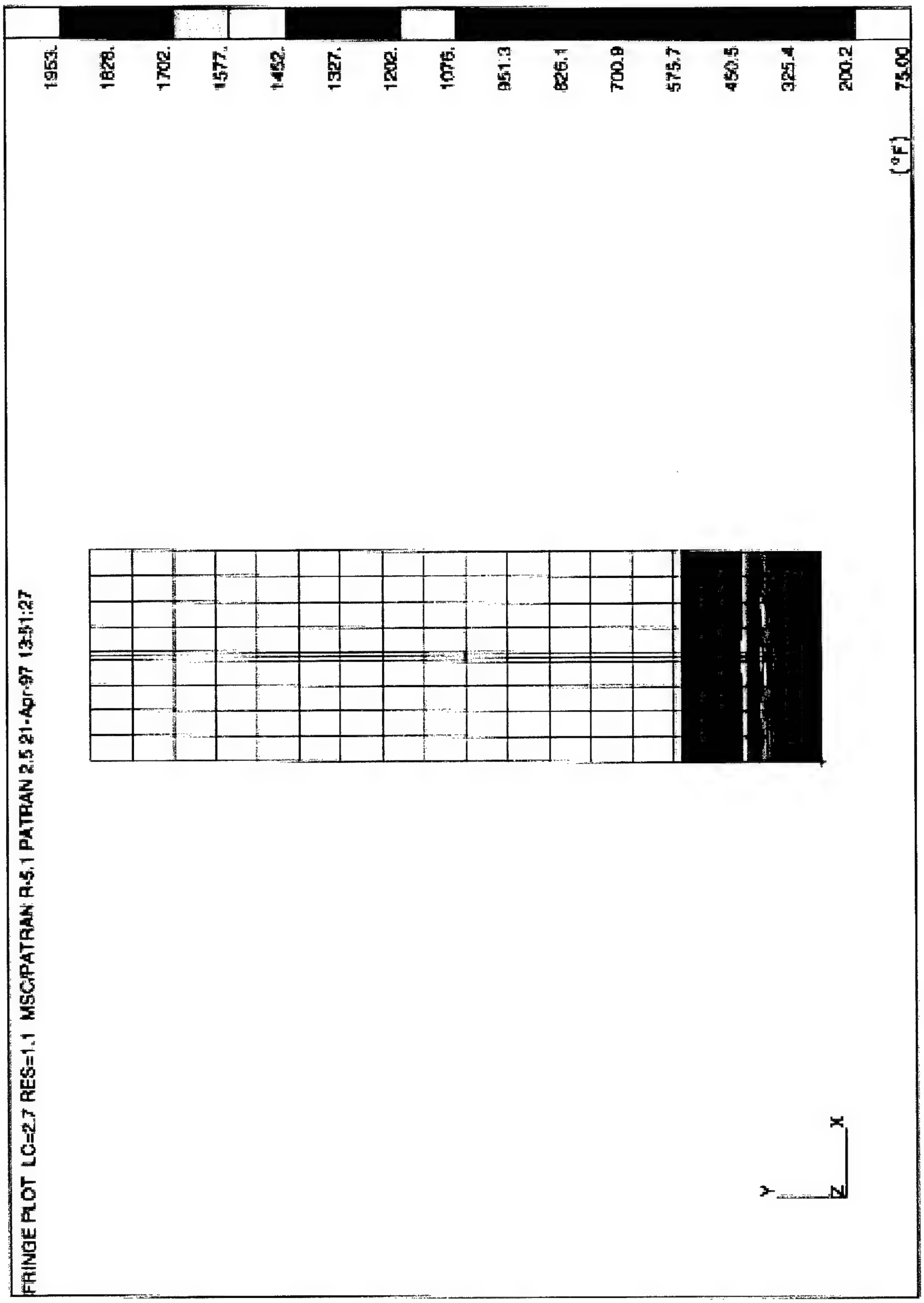

Figure 13. Red River Igloo Roof at 7hr, Spalling Temp. 1700°F

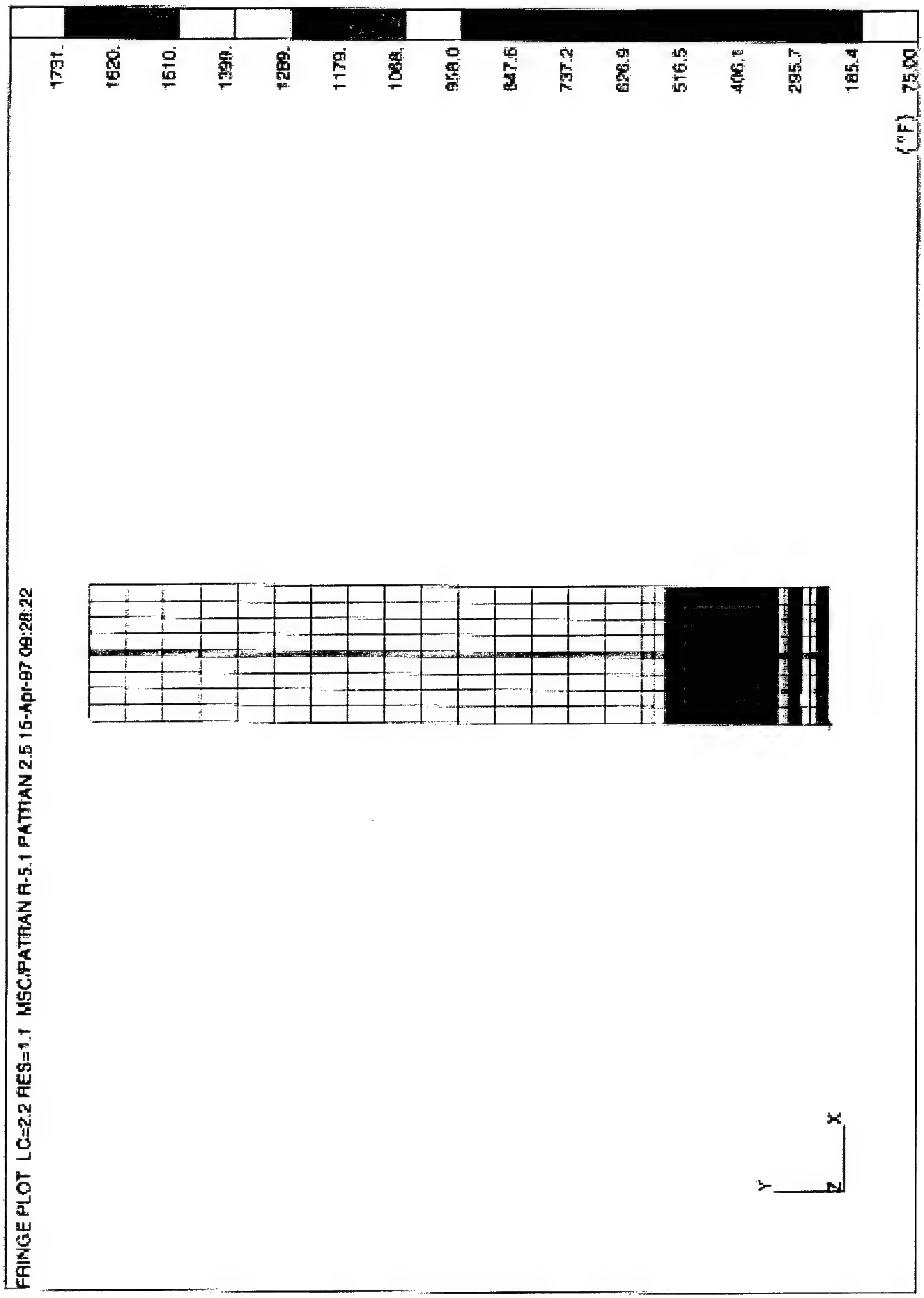

Figure 14. Red River Igloo Wall at 12 hr. Spalling Temp 1700°F

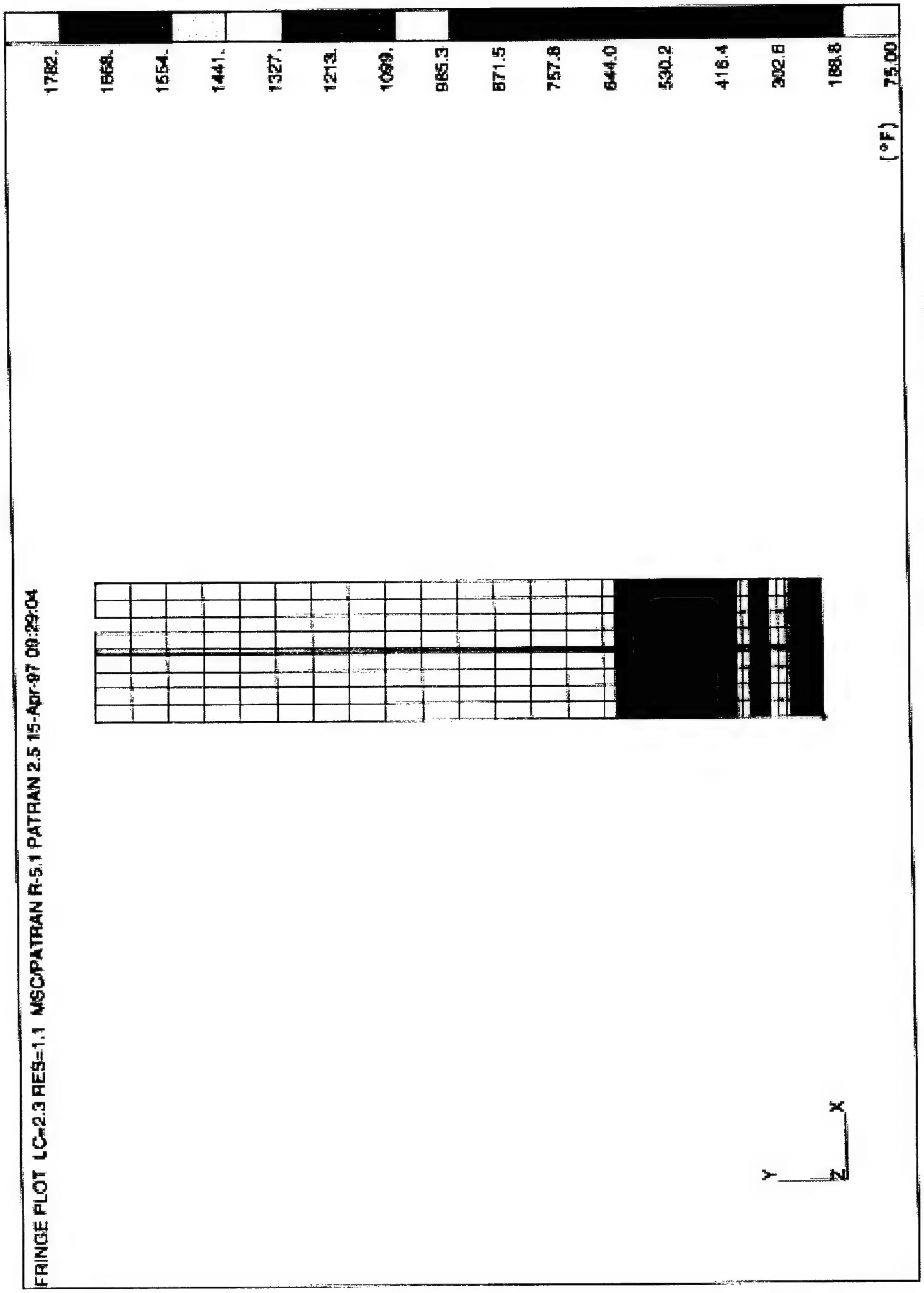

Figure 15. Red River Igloo Wall at 24hr, Spalling Temp. 1700°F

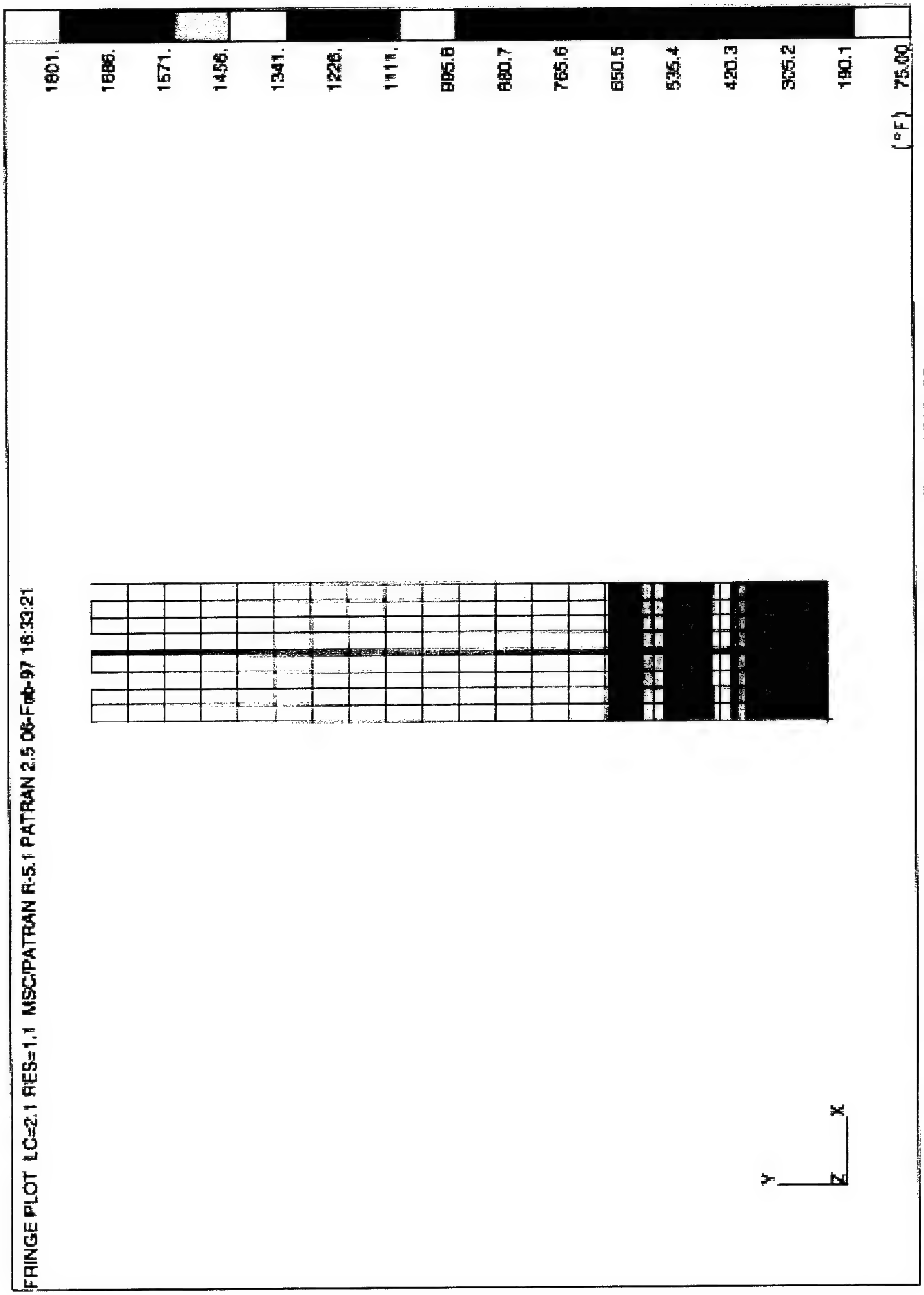

Figure 16. Red River Igloo at 48hr. Spalling Temp 1700 °F

Figure 17. Internal View of Red River Igloo After The Fire.

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